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December 2020

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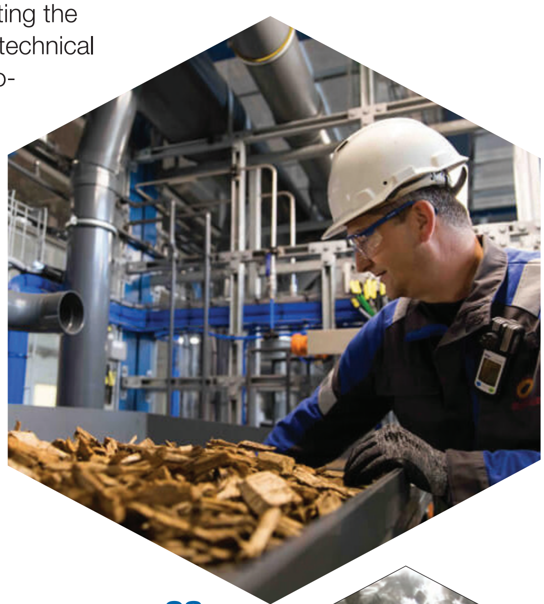
Cover Story

In the News



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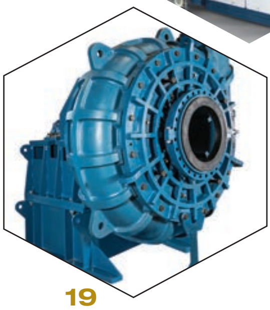

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Coming in January

Look for: **Feature Reports** on Fire & Explosion Protection; and Solids Drying; A **Focus** on Flow Measurement & Control; A **Facts at your Fingertips** on Materials of Construction; a **Newsfront** on Emissions Control; **New Products**; and much more

Cover design: Tara Bekman

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Editor's Page

Looking ahead

This has certainly been a year to remember, and as 2020 comes to an end this month, I expect we are all looking forward to the new year with hope. There are encouraging signs for better days to come. While at the time of this writing, the coronavirus is taking a strong hold again this fall, we have also received welcome news about effective vaccines on the horizon. And for the chemical process industries (CPI), third quarter financial reports are showing signs of recovery. Kevin Swift, chief economist at the American Chemistry Council (ACC; www.americanchemistry.com) says that "With six consecutive months of gains, the October CAB [Chemical Activity Barometer] reading remains consistent with recovery in the U.S. economy." The CAB is a leading economic indicator created by the ACC. For an update on the economic outlook, join us this month as Kevin Swift presents the latest information in a webcast, scheduled for December 15. Details can be found on www.chemengonline.com.

Technology trends

While the CPI include a wide variety of processes and products, there are a number of common trends that we expect to continue to grow in the coming year and beyond.

Digitalization. By creating situations that called for quick response times to changing production and supply needs, along with the need for more remote activities, the pandemic has accelerated the adoption of digital technologies. The use of virtual and augmented reality, digital twins, data analytics and more is growing. Robotics, for example, which have been used to carry out mundane repetitive tasks in discrete manufacturing, are now increasingly being used for tasks where safety is a concern, such as in tank inspections and more. And with advances in artificial intelligence and machine learning, robotics are finding applications in much more advanced tasks in the CPI. See our Newsfront on robotics in this issue for more on this.

Sustainable chemistry. The CPI have been reporting on sustainability goals for some time, and focus in this area is intensifying as concerns about climate change and the environment by consumers, investors, governments and corporations grow. The CPI are involved in many sustainability initiatives, just one example of which is the "Carbon Partnership Report 2020: Sustainability through Sports" issued by Dow (www.dow.com) last month. Several areas with high activity include the following:

Alternative energy sources. The CPI are active in the overall energy transition, including work on energy storage and other contributions to renewable energy efforts, such as materials for solar panels. And as reported in this column last month, there is a strong push to develop green hydrogen as well as carbon capture technologies.

Alternative raw material and process routes to the traditional petroleum-based routes. This month's cover stories explore some of the best practices and advances in bioprocessing, which is one route companies are taking toward a circular economy.

Recycling technologies. Attention to the impact that plastic waste is having on our environment has fueled advances in recycling technologies that include new approaches to mechanical and chemical recycling. Numerous alliances and collaborations have formed to address recycling challenges.

As technologies in these and other areas continue to advance, we look forward to continuing to bring this information to you in the new year. ■

Dorothy Lozowski, Editorial Director

Edited by:
Gerald Ondrey

DESALINATION

The challenge for large-scale desalination is to improve the performance of membranes used for reverse osmosis. One promising method is to introduce artificial water channels (AWCs) into synthetic membranes, to imitate the aquaporins of biological proteins for transporting water. Although AWCs have been a research topic for many years, large-scale performance has not been feasible under the harsh osmotic pressure and salinity conditions. Now, a hybrid approach that combines a polyamide matrix and AWCs into a single structure has been developed by an international team of researchers from Saudi Arabia (KAUST) and Italy (Politehnico di Torino) and coordinated by scientists from the Institut Européen des Membranes (IEM; Montpellier, France; www.iemm.univ-montp2.fr).

Their membranes, which take the form of a sponge superstructure, have been tested under industrial conditions and shown to outperform conventional membranes, as reported in *Nature Nanotechnology* last month. According to the article, these biomimetic membranes can be easily scaled for industrial standards, provide 99.5% rejection of NaCl or 91.4% rejection of boron, with a water flux of 75 $Lm^{-2}h^{-1}$ at 65 bars and 35,000 ppm NaCl feed solution, representative of seawater desalination. "This flux is more than 75% higher than that observed with current state-of-the-art membranes with equivalent solute rejection, translating into an equivalent reduction of the membrane area for the same water output

(Continues on p. 6)

Nanoengineered catalysts can upcycle polyethylene . . . .

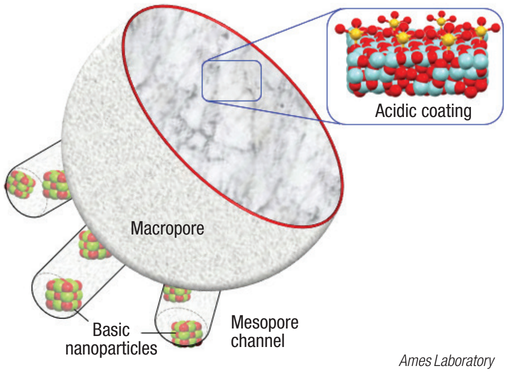
Drawing inspiration from the enzymatic breakdown of macromolecules in cellular systems, scientists at Ames Laboratory (Ames, Iowa; www.ameslab.gov) have developed a nanostructured catalyst that can break down high-density polyethylene (HDPE) and other polyolefins into a narrow distribution of diesel- and lubricant-range alkanes via selective hydrogenolysis. The development could be important in the quest for viable approaches to recycling single-use plastic waste.

The newly developed nanocatalyst consists of a platinum core, surrounded by mesoporous silica nanoparticle channels (diagram). Long polymer chains thread through the silica pore channels to reach active sites on the Pt core. The catalyst's structured design and size enable the nanoparticles to hold onto and cleave the longer polymer chains into consistent, uniform shorter hydrocarbons that have the most potential to be upcycled into useful end products.

"This type of controlled catalysis process has never before been designed based on inorganic materials," says Wenyu Huang, associate professor of chemistry at Ames Lab.

Huang's research team used solid-state nuclear magnetic resonance (NMR) to study the interactions between the polymer chains and the catalyst. As the team of scientists note, the NMR studies revealed that "long hydrocarbon macromolecules readily move within the pores of this catalyst, with subsequent escape being inhibited by polymer-surface interactions."

This behavior resembles the binding and translocation of biological macromolecules in the catalytic cleft of processive enzymes (those that catalyze consecutive reactions without releasing the substrate, such as DNA polymerase). Simlarly, the hydrogenolysis of polyethylene with the new catalyst proceeds processively to yield a reliable, narrow and tunable stream of alkane products. "We were able to show that the catalytic process is capable of performing multiple identical decon-



Ames Laboratory

struction steps on the same molecule before releasing it," Huang says.

This research project will be expanded and continued under the direction of the Institute for Cooperative Upcycling of Plastics (iCOUP), led by Ames Laboratory.

. . . and convert mixed, impure waste to biodiesel

In another example of a biologically inspired and nano-engineered catalyst, researchers at RMIT University (Melbourne, Australia; www.rmit.edu.au) have developed ceramic catalyst particles with a porous network organized hierarchically, where one chemical reaction takes place within larger pores, while a second transformation occurs in the smaller pores.

The porous ceramic framework, which the researchers say is inexpensive to manufacture, allows a precise way of performing multiple reactions in a set sequence. Also, the compartmentalization of the active-site environments and substrate channeling protects the active sites from impurities, allowing the catalyst to be used to convert a highly impure feedstock, such as used cooking oils, into a valuable product, such as biodiesel fuels.

To achieve the transformation from mixed feedstock to diesel fuel, the macropores of the catalyst material are selectively functionalized with a sulfated zirconia solid-acid coating, while the smaller mesopores are selectively functionalized with MgO solid-base nanoparticles. Co-lead investigator Karen Wilson, of RMIT, said the new catalyst design mimicked the way that enzymes in human cells coordinated complex chemical reactions. Previously developed catalysts can perform multiple simultaneous reactions, she says, but "the approaches offered little control over the chemistry and tend to be inefficient and unpredictable."

The next steps for the RMIT research team are to scale up the catalyst fabrication from grams to kilograms, and to adopt 3D-printing technologies to accelerate commercialization. The team is looking for business partners to create a range of commercially available catalysts for different applications.

and a roughly 12% reduction of the required energy for desalination," according to the abstract. The technology has been patented.

SULFURIC ACID CATALYST

Haldor Topsoe A/S (Lyngby, Denmark; www.topsoe.com) has introduced a new catalyst for converting SO_2 into sulfuric acid. VK38+ is a new potassium-promoted catalyst that has been proven to have higher activity than any other commercial potassium-promoted catalyst, regardless of which converter bed it is used in. The catalyst has already been demonstrated in two industrial plants. Through its higher activity, VK38+ has the potential for enhanced performance, higher efficiency and reduced climate footprint. VK38+ provides these performance results without the cost increases that are associated with many Cs-catalyst solutions, says Topsoe. Calculations for VK38+ show an up to 40% reduction of long-term catalyst spending and a payback time of just a few months.

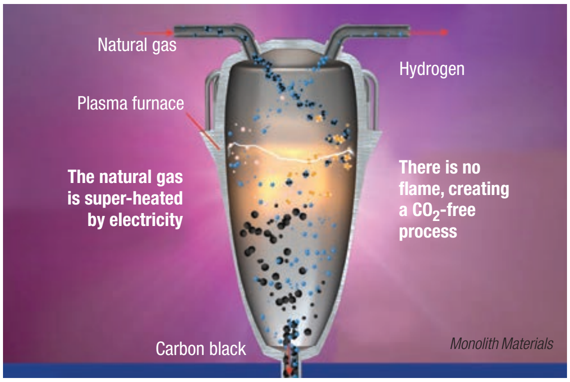
TS-1 CATALYST

Titanium silicalite-1 (TS-1) has been used for nearly 40 years for the catalytic conversion of propylene and hydrogen peroxide into propylene oxide (PO), but the mechanism for the conversion has not been well understood. Now, a team of researchers from BASF SE (Ludwigshafen, Germany; www.basf.com), ETH Zurich (Switzerland), the Uni-

(Continues on p. 7)

Methane pyrolysis process uses renewable electricity to split CH_4 into H_2 and carbon black

Site commissioning is underway at a facility in Nebraska that uses plasma pyrolysis to generate hydrogen gas and carbon black from natural gas without any local carbon dioxide emissions. The developer, Monolith Materials (Lincoln, Neb.; www.monolithmaterials.com), scaled up the process at the site after operating a pilot plant from 2014 to 2018.



In a second phase of the project, currently in the front-end engineering and design (FEED) stage, the pyrolysis-derived H_2 will be combined with N_2 from the atmosphere to make ammonia for agricultural fertilizer via a Haber-Bosch process.

In Monolith's proprietary methane-pyrolysis process, natural gas is fed into a reactor along with other process gases, where it is heated to between 1,500 and 2,000°C by electric plasma. The heat splits the CH_4 into H_2 and solid carbon in the absence of O_2. "The reaction conditions, with close attention on the fluid dynamics of the gases and the aerodynamics of the solids, allow us to finely control the particle morphology of the carbon black at the nanoscale, and also to avoid unwanted side reactions," explains Rob Hanson, co-founder and CEO of Monolith.

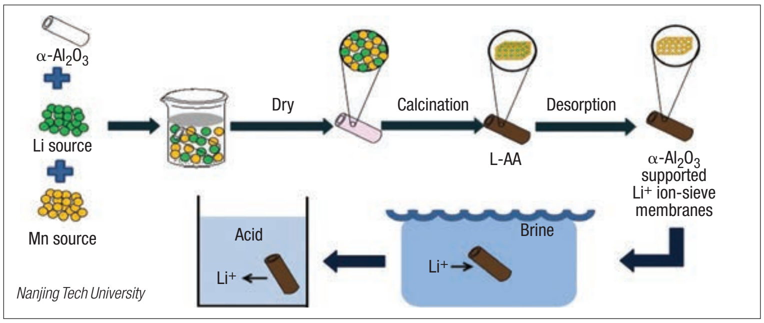
To achieve H_2 production at commercial scale, the company met the challenge of running the plasma pyrolysis reactor reliably for long periods at the high temperatures required for methane splitting. The carbon black produced by the reaction is sold into the vehicle tire market and used for battery materials, while the H_2 could be used for ammonia or in the petroleum-refining industry.

The environmental advantages of the electric plasma-pyrolysis process are significant. Production of H_2 in this way uses only one-seventh the power required to produce H_2 via conventional electrolysis of water, and purified water is not required. And if the electricity to generate the plasma comes from renewable sources, it would allow fully emissions-free production of H_2. Natural gas for the process could also be sourced from landfill biogas, Hanson notes.

Full commercial-scale production of what is termed "turquoise ammonia" (NH_3 produced using H_2 from methane pyrolysis) at the facility is expected in 2024.

Tubular sieves for extracting lithium from brines

Researchers from the College of Chemical Engineering, Nanjing Tech University (Nanjing, China; www.njtech.edu.cn) have developed a new strategy for forming lithium ion-sieve membranes to achieve an efficient recovery of lithium ions from brine or seawater.



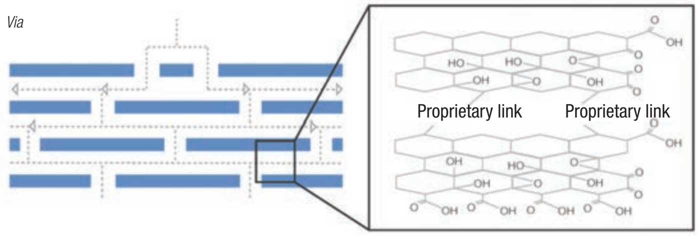
Spinel lithium manganese oxide ion-sieves have been considered the most promising adsorbents to extract Li^+ from brines or seawater. The researchers have reported a lithium ion-sieve which was loaded onto tubular alpha-Al_2O_3 ceramic substrates by dipping crystallization and post-calcination (diagram).

The lithium manganese oxide ($Li_4Mn_5O_{12}$) was first synthesized onto tubular alpha-Al_2O_3 ceramic substrates as the ion-sieve precursor and the corresponding lithium ion-sieve was obtained after acid pickling. The lithium manganese oxide could be uniformly loaded not only onto the surface of alpha-Al_2O_3 substrates but also inside the pores. The equilibrium adsorption capacity of the lithium ion-sieve was 22.9 mg/g. The adsorption balance was reached after 12 hours. After five adsorption cycles, the adsorption capacity of the lithium ion-sieve was 60.88% of the initial capacity.

For the dynamic adsorption-desorption process, the lithium ion-sieve exhibited excellent adsorption performance for Li^+, with the Li^+ adsorption capacity of 9.74 mg/g and a manganese ion (Mn^{2+}) dissolution loss rate of 0.99%. After three dynamic adsorption-desorption cycles, 80% of the initial dynamic adsorption capacity was still maintained.

Graphene-oxide filtration membrane for harsh chemical environments

Filtration is being investigated as an alternative to thermal separation methods (such as distillation and evaporation) in many applications because of the potential energy savings, but conventional filtration membranes, such as those used in water desalination, are often not robust enough to withstand high temperatures and harsh chemical conditions.



Now, Via Separations (Somerville, Mass.; www.viaseparations.com) has demonstrated a process for making graphene-oxide (GO) membrane material that can withstand harsh conditions. In its first commercial application, the GO membrane is being employed for the concentration of black liquor in pulp-and-paper operations, where the membrane experiences very high pH.

A byproduct from wood-pulping processes, black liquor contains lignin, hemicellulose and inorganic materials from wood, after cellulose has been removed during paper manufacturing. Initially, the black liquor contains about 12–15% solids, and it needs to be concentrated to 70% solids in order to recover and recycle the organic chemicals from the black liquor back into the pulping process.

Via's membrane consists of graphene-oxide (GO) flakes cast onto a hydrophilic support material through a proprietary deposition procedure. The resulting scaffold of GO flakes is bound together by customizable molecular links that allow the scientists to manipulate the amount of space between the GO sheets. "The assembly process with the GO and linkages can be run in a variety of ways," explains Via engineer Lauren Kovacs. "The GO chemistry allows for customizations to separate materials with varying molecular weights."

The resulting membrane is robust enough to separate solids at pH levels of 13–14. The membrane material is then spiral-wound into modules similar to the configuration of a reverse-osmosis membrane.

Via engineers are building a portable pilot system for black liquor concentration that will be set up at a paper mill in early 2021.

This additive reverses the effects of aging in recycled asphalt pavement

A new rejuvenator technology aims to improve the chemistry and service life of recycled asphalt pavement (RAP). The Invigorate additive, developed by Colorbiotics (Ames, Iowa; www.colorbiotics.com) based on Iowa State University research (www.iastate.edu), helps overcome issues with asphaltene aggregation and oxidation, which occur as RAP ages, and enables mixtures with more recycled content. "When asphalt ages, oxygen becomes permanently fused to the surfaces of asphaltene agglomerates. This accounts for a large part of cracking susceptibility and also impacts the ability of RAP to mix well with virgin asphalt concrete (AC) at a molecular level. Invigorate's solvency breaks apart these agglomerates, and its chemical functionality permanently binds to the oxidized sites. The Invigorate-asphaltene complexes are more compatible with the virgin AC and are stabilized against reagglomeration," explains Eric Cochran, professor of chemical and biological engineering at Iowa State. Produced from soybean-oil feedstock, Invigorate is unique in the marketplace in that it triggers chemical reactions within the RAP, rather than acting superficially, and is able to balance viscosity, solvency and reactivity to aggressively target oxidized asphaltenes, adds Cochran. Invigorate's performance benefits mean that mixtures incorporating as much as 50% RAP can meet necessary specifications, greatly improving upon current industry-standard mixtures of 20–25% RAP.

While the sustainability benefits of increasing RAP content are clear, there are also durability considerations at higher RAP levels, says Dan Staebell, Colorbiotics' asphalt business development manager. "Using RAP is environmentally and economically smart, but we have to be mindful of long-term durability when increasing to higher levels near 50%. This can be achieved and confirmed using the balanced-mix design approach. Contractors and officials across the U.S. are researching and understanding these tools and implementing them to assist in specification decisions," says Staebell. Invigorate is currently undergoing a number of field trials across the U.S. wherein users have found the asphalt mixtures with higher RAP content very workable, even in colder conditions, according to Staebell.

versity of Cologne and the Fritz Haber Institute (Berlin, both Germany) have used a variety of tools to unveil this mechanism, which was reported last month in *Nature*.

TS-1 is a microporous, crystalline material made up of silicon and oxygen, with small amounts of titanium. Up to now, experts assumed that the active center in TS- 1 contains individual, isolated titanium atoms. Combining solid-state nuclear-magnetic resonance (NMR) studies with computer modeling, the team was able to show that two neighboring titanium atoms are required to explain the catalytic activity, rather than isolated Ti atoms.

The team believes the findings will not only help to improve existing catalysts, but also to develop new homogeneous and heterogeneous catalysts.

MEMBRANES

Last month, Mann+Hummel (Ludwigsburg, Germany; www.mann-hummel.com) expanded its Life Sciences & Environment (LS&E) efforts by investing in ZwitterCo (Somerville, Mass.; www.zwitterco.com), an early-stage company developing membranes for handling waste streams heavily contaminated with organic materials. The investment, through Mann+Hummel Corporate Ventures, will boost commercialization efforts of this technology for wastewater-treatment applications. The strategic partnership between the two companies will be handled through Microdyn-Nadir US, Inc. (Goleta, Calif.; www.microdyn-nadir.com), operating as part of the LS&E group within the Membrane Solutions segment.

Earlier this year, ZwitterCo started a two-year, $1.25-million project funded under the of the U.S. Dept. of Energy's (DOE) Water Security Grand Challenge. That project aims to demonstrate ZwitterCo's

(Continues on p. 8)

membrane technology for the pretreatment of produced water in the Permian Basin in southwestern U.S.

ZwitterCo's membrane technology is based on zwitterionic copolymers that can reject key components from produced water while maintaining immunity to detrimental and irreversible membrane fouling. The membranes can remove nanoscale oils, greases, colloidal material, heavy metals and dissolved organic compounds without removing salts and dissolved solids. This makes filtration of highly saline waste streams practical and cost effective, according to DOE's National Energy Technology Laboratory (Morgantown, W.Va.; www.netl.doe.gov).

MOF FILMS ON PLASTIC

Despite a growing interest in metal-organic frameworks (MOFs), researchers have yet to establish an effective method for forming MOFs into thin films. Most studies on MOF preparation focus exclusively on the powdered form. Forming MOFs into thin films would open up its use for humidity sensing, gas sensing and resistive switching devices.

Researchers from Tohoku University (Sendai; www.tohoku.ac.jp), Iwate University (Morioka) and the Japan Synchrotron Radiation Research Institute (JASRI; Hyogo, all Japan) overcame this obstacle by controlling the growth of MOF into films using a simple "layer-by-layer" method. This involved the sequential immersion of substrates into ingredient solutions. The researchers used four common plastics as substrates for the films, including nylon and acrylic resin. Further studies on the film-growing mechanism are expected to provide important insights into their coating on flexible and transparent plastic substrates under ambient conditions.

PASSIVE COOLING

Researchers from the Dept. of Materials Science and Engineering at the Massachusetts Institute of Technology (MIT; Cambridge; www.mit.edu) have developed a new two-layered material that mimics the cooling behavior of camel fur, which could provide extended cooling to preserve perishable goods without using external refrigeration or power. The new material has a bottom hydrogel layer that mimics the camel's sweat glands. This gelatin-like substance consists mostly of water contained in a sponge-like matrix. The water can evaporate from the hydrogel, thereby lowering the temperature. The hydrogel is covered with an upper layer of aerogel, which acts as the camel's fur by insulating against external heat while allowing the vapor to pass through.

Field tests and detailed analysis have shown that this new two-layer material, less than a half-inch thick, can provide cooling of more than 7°C for five times longer than the hydrogel alone — more than eight days versus less than two, says MIT. The findings were described in the journal *Joule* last month.

The researchers say the system could be used for food packaging to preserve freshness, as well as for keeping medicines, such as vaccines, safe when delivered to remote locations. ❑

Sustainable graphite pilot project kicks off in Canada

A new project in Canada will build a pilot facility to demonstrate a carbon-neutral production strategy for battery-grade graphite materials. Nouveau Monde Graphite (Saint-Michel-des-Saints, Québec, Canada; www.nouveaumonde.ca) has signed an agreement with Olin Corp. (Clayton, Mo.; www.olin.com) to construct two commercial-scale graphite-purification furnaces within Olin's existing facility in Bécancour, Québec, which also enables the project to leverage the area's extensive hydropower infrastructure. Nouveau Monde Graphite has developed a proprietary thermochemical process, which employs Olin's chlorine-based products, and enables graphite purity levels exceeding 99.95%, explains Eric Desaulniers, founder, president and CEO of Nouveau Monde Graphite. The process has been tested at laboratory scale, and also at commercial levels using adapted third-party equipment. According to Desaulniers, the access to hydropower is the key differentiator for the project, which will harness this clean energy source to power the world's first all-electric graphite-extraction operation at an open-pit mine, enabling a vertically integrated, low-carbon operation from graphite ore to battery-grade anode material.

Commissioning of the purification furnaces is scheduled for mid-2021, with an initial nameplate capacity of 1,500 metric tons per year (m.t./yr) of battery-grade graphite. Following an initial optimization phase, the company expects to reach full commercial production on 200,000 m^2 of land adjacent to Olin's property. "Nouveau Monde targets, with its modular approach, 40,000 m.t./yr production of anode material for the initial phase, with the option to reach 100,000 m.t./yr of conversion capacity as demand increases in the battery and specialty markets," says Desaulniers, emphasizing that the company's commercial plant will be carbon-neutral and will repurpose co-products from its operation, further validating the end products' sustainability.

Endress+Hauser establishes internet security standards

The cryptography working group within the Internet Engineering Task Force (IETF; Fremont, Calif.; www.ieft.org) standards organization has chosen the CPace protocol — developed by Endress + Hauser AG (Reinach, Switzerland; www.endress.com) — as a recommended method for use in internet standards. After undergoing extensive security analyses, the CPace protocol emerged as the winner in a competition among submissions from developers at several well-known companies.

Secure access to field instruments is of the highest priority for operators across all branches of the chemical process industries (CPI). Modern plants contain hundreds or thousands of measurement and control instruments that must be accessed remotely with growing frequency. These field instruments also have to be installed, monitored or serviced on a regular basis. Secure password-based user authentication plays a special role today, especially when devices with digital interfaces are involved.

In order to utilize Bluetooth communications technology in industrial environments, security experts at Endress+Hauser identified a need for additional protection. The result was the development of a solution called CPace (composable password-authenticated connection establishment), which belongs to the class of PAKE (password-authenticated key exchange) methods. Among other things, PAKE technology is used with the German electronic ID cards as a means of largely decoupling the cryptographic security level from the length of the password. The advantage of CPace is that the processing power of even the smallest of field instruments is sufficient to provide devices, and thus the industrial systems, with the best level of protection against cyberattacks. At the same time, CPace enjoys a high degree of acceptance among users, because the desired level of security can be achieved without relying on long passwords. ■

Business News

Plant Watch

Momentive to expand production of polyurethane additives in Italy

November 12, 2020 — Momentive Performance Materials Inc. (Waterford, N.Y.; www.momentive.com) will invest $13 million to expand its plant in Termoli, Italy to create a large manufacturing hub for polyurethane additives. The modernized facility will supply customers in Europe, Russia and Turkey. Full commercial production is expected by the middle of 2022.

Mitsui Chemicals completes construction of new synthetic-fluids plant

November 12, 2020 — Mitsui Chemicals, Inc. (Tokyo, Japan; www.mitsuichemicals.com) has completed the construction of a new plant to produce Lucant, a series of hydrocarbon-based synthetic fluids, in Chiba Prefecture, Japan. Commercial operation of the new plant is expected to begin in April 2021. Lucant is said to be the world's first commercially available high-performance hydrocarbon-based synthetic oil.

Covestro expands its production capacity for Vulkollan raw materials in Thailand

November 12, 2020 — Covestro AG (Leverkusen, Germany; www.covestro.com) has started construction of a new production plant for Vulkollen elastomer raw materials in the Map Ta Phut industrial zone in Thailand. Production at the new plant is scheduled to start at the end of 2022. Vulkollen elastomers are mainly used in applications where high mechanical strength and abrasion resistance are required.

Commissioning begins on Evonik polyamide-12 plant

November 9, 2020 — Evonik Industries AG (Essen, Germany; www.evonik.com) has completed construction and begun commissioning at its €400-million polyamide-12 plant in Marl, Germany. Evonik expects to commission additional plants in Marl by the first quarter of 2021, with full completion expected in the first half of 2021. With the additional plants for polyamide 12 and its precursors being built at the Marl Chemical Park, alongside existing facilities at the site, Evonik will increase its overall capacity for the polymer by more than 50%.

Wacker invests in new production line for silicone specialties

November 9, 2020 — Wacker Chemie AG (Munich, Germany; www.wacker.com) plans to construct a new production line for silane-terminated polymers at its site in Nünchritz, Germany. The production line, which will significantly expand Wacker's production capacities for hybrid polymers, will go onstream in 2022.

CF Industries announces 'green' ammonia project in Louisiana

November 2, 2020 — CF Industries Holdings, Inc. (Deerfield, Ill.; www.cfindustries.com) announced plans for a green ammonia project at the company's Donaldsonville Nitrogen Complex in Louisiana, which will produce approximately 20,000 metric tons per year (m.t./yr) of green ammonia. The company will install an electrolysis system to generate carbon-free hydrogen that will then be supplied to an existing plant to produce ammonia.

Lubrizol and Grasim Industries partner for CPVC resin plant

November 2, 2020 — Lubrizol Corp. (Wickliffe, Ohio; www.lubrizol.com) and Grasim Industries Ltd. (Mumbai, India; www.grasim.com), a company of the Aditya Birla Group, will jointly manufacture chlorinated polyvinyl chloride (CPVC) resin at a nearly 100,000-m.t./yr plant at Grasim's site in Vilayat, Gujarat, India. Once operational in 2022, this plant will represent the largest single-site capacity for CPVC resin production globally.

Preem begins conversion of Lysekil refinery for renewable-fuels production

October 26, 2020 — Preem AB (Stockholm, Sweden; www.preem.com) has begun a major conversion project at its petroleum refinery in Lysekil, Sweden, which will rebuild the site to become Scandinavia's largest producer of renewable fuels. In an initial phase, Preem plans to carry out a redevelopment of the existing Synsat diesel plant, which will increase Preem's renewable diesel production by around 650,000–950,000 m^3/yr. The modified plant is expected to be operational by 2024.

Celanese to add new production line for UHMW-PE at Bishop, Texas site

October 23, 2020 — Celanese Corp. (Dallas, Tex.; www.celanese.com) added a new production line for ultra-high-molecular-weight polyethylene (UHMW-PE) at its Bishop, Texas manufacturing facility. This new production line is expected to add approximately 15,000 m.t./yr of production capacity by the start of 2022.

Repsol to build Spain's first advanced biofuels plant

October 23, 2020 — Repsol S.A. (Madrid, Spain; www.repsol.com) will build Spain's first production plant for advanced biofuels at its Cartagena refinery, which will supply 250,000 m.t./yr of advanced biofuels. The new facility, construction of which will represent an estimated investment of €188 million, will include the commissioning of a hydrogen plant that will supply a new hydrotreatment unit.

LINEUP

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CELANESE
CF INDUSTRIES
COVESTRO
EVONIK
GRASIM
HUNTSMAN
INDORAMA
LINDE ENGINEERING
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Mergers & Acquisitions

Grasim to divest its fertilizers business to Indorama

November 12, 2020 — Grasim Industries plans to divest its fertilizer business, IndoGulf Fertilizers (IGF) to Indorama India Pvt. Ltd. IGF handles the manufacture, trading and sale of urea, customized and specialty fertilizers, agricultural inputs and crop-protection, plant and soil-health products.

Neste to acquire Bunge refinery site in Rotterdam

November 9, 2020 — Neste Corp. (Espoo, Finland; www.neste.com) will acquire Bunge Loders Croklaan's refinery, located in Rotterdam, the Netherlands, for €258 million. The acquired plant is located next to Neste's existing biorefinery. The site has a pipeline connection to Neste's site. The transition will be implemented in phases, with the refinery plant's full pretreatment capacity available for processing Neste's feedstock by the end of 2024.

Baker Hughes to acquire carbon-capture specialist 3C

November 9, 2020 — Baker Hughes Co. (Houston; www.bakerhughes.com) announced that it is acquiring Compact Carbon Capture (3C), a technology-development company specializing in carbon capture solutions. 3C's technology differs from traditional solvent-based carbon-capture solutions by using rotating beds instead of static columns.

Showa Denko establishes high-purity gases JV in China

November 9, 2020 — Showa Denko K.K. (SDK; Tokyo, Japan; www.sdk.co.jp) and Chengdu Kemeite Special Gas Co. have established a new joint venture (JV) in Chengdu, China, focused on manufacturing high-purity gases for electronics, such as tetrafluoromethane (CF_4). The new company will start its operation in January 2021.

Siemens and Linde partner to accelerate decarbonization efforts

November 6, 2020 — Siemens Energy (Munich, Germany; www.siemens-energy.com) and Linde Engineering (Pullach, Germany; www.linde.com) entered into a strategic partnership to enhance the sustainability and performance of petrochemical facilities. The companies will jointly explore how to facilitate decarbonization through emissions reductions and increases in energy efficiency.

Huntsman to divest adhesives business in India

October 29, 2020 — Huntsman Corp. (The Woodlands, Tex.; www.huntsman.com) agreed to sell its India-based consumer adhesives business, part of the Advanced Materials division, to Pidilite Industries Ltd. in an all-cash transaction valued at up to $285 million.

NOVA Chemicals to sell expandable styrenics business to Alpek

October 20, 2020 — NOVA Chemicals Corp. (Calgary, Alb., Canada; www.novachem.com) will sell its expandable styrenics business to Alpek S.A.B. de C.V. (San Pedro Garza Garcia, Mexico; www.alpek.com). NOVA's expandable styrenics business includes manufacturing plants in Pennsylvania and Ohio, along with commercial operations in Asia. ■

Mary Page Bailey

AI and Position-Sensing Drive Robotics Expansion

Advancements in artificial intelligence (AI) and improved technologies for providing robots with positional awareness have driven an expansion of robotics use in a variety of application areas across the chemical process industries (CPI)

Robots have been fixtures on discrete-product manufacturing assembly lines for some time, but they have not seen the same level of penetration into chemical manufacturing. In part, this is because the nature of chemical manufacturing and the complexity and diversity of chemical processes have not lent themselves to the incorporation of robots to the same degree as discrete manufacturing. Now, however, recent developments in a range of different fields, such as artificial intelligence (AI), image analysis and others, have expanded the possible applications for which robots can be deployed. Several new robotics applications can have a significant impact on operations in the CPI.

Many of the emerging applications for robots at chemical process facilities involve functions known to be dangerous, difficult or time-consuming for humans to carry out. These include using robots for asset inspections, warehousing, plant security, chemical and materials R&D, picking and sorting operations, among others.

The expansion of robotics at CPI sites is part of a broader trend in automation, and is tied closely to the so-called digital transformation that seeks to incorporate digital tools to improve plant operations. In general, digitalization technologies are being inegrated with automation and robotics tools with the goal of increasing plant safety, reliability and profitability.

Technology convergence

While effective at repetitive movements, industrial robots have historically been limited in those applications that require data collection from the surroundings, autonomous movement and decision-making in direct collaboration with humans.

Xiao Zhong, a research analyst with Lux Research Inc. (Boston, Mass.; www.luxresearchinc.com), explains, "Robotics in the CPI has been driven by advancements in the ability of robots to better sense and respond to their environment and their position relative to other objects and humans." In addition to improved machine-learning algorithms, these advancements include better camera systems, image analysis capabilities, light detection and ranging (LiDAR), sensors, grippers for delicate objects and others, adds Josh Kern, another Lux analyst.

FIGURE 1. Combining artificial intelligence and robotics, IBM developed a system to accelerate the discovery of new materials

And the improved technologies, along with growing AI know-how and improved automation tools, are coming together to increase the scope and impact of robots in the CPI.

"Integration is fundamental to maximizing outcomes when deploying robotics," says Sergio Fernandes, chemical market leader at Yokogawa Corp. of America (Sugar Land, Tex.; www.yokogawa.com). "The data captured by robots become an additional and integral piece of the 'data lake.' Not only are we talking about process variables (temperature, pressure, flow, pH, composition), but also about non-numeric data, like images and speech. The expectation now is for AI algorithms to digest photos and dialogue, and to infer from their pattern what may turn into personnel safety concerns, environmental compliance risk, physical asset integrity and health, and, ultimately, operational profit sustainability," explains Fernandes.

Yokogawa's approach to creating a platform for integrating robotics and digitalization tools with domain expertise in the CPI depends on all of these. "Advancements in sensing and micro-electromechanical technologies make robots more functional, less expensive, smaller and lighter. Autonomous vehicle research and development has lowered costs of high-priced technology testbeds. The convergence of all these technologies turned robotics into one of the main beneficiaries," says Yokogawa's Fernandes.

Meanwhile, ongoing workforce challenges in the CPI and the current pandemic situation has further amplified the opportunities to explore robotics in various applications. "CPI companies are looking for ways to

FIGURE 2. The remote-operated climbing robots from Invert Robotics can climb the walls of tanks, vessels and reactors for visual inspection

replace retiring workers, while navigating a complex and fast-changing network of end-use markets," explains Duane Dickson, vice chair and leader of chemicals and oil and gas at Deloitte LLP (London, U.K.; www.deloitte.com). "This is creating imperatives to adopt new ways of operating, and companies are looking to technologies, such as robots and automation, to help them do so as they head into the future."

In addition, the fallout from the COVID-19 pandemic has accelerated the rate of adoption for digital tools, including AI-enabled robots, by 5 to 10 years, Dickson estimates.

Chemical and materials R&D

The intersection of robotics and AI is playing out significantly in the area of research and development. According to Kebotix Inc. (Cambridge, Mass.; www.kebotix.com) CEO Jill Becker, the process of devising and synthesizing new molecules and materials has not changed fundamentally for a century or more, and a more modern approach is required to solve today's challenges.

In pursuit of this, Kebotix has built a robotics- and AI-powered, self-driving laboratory for materials discovery. The company says its system can "accelerate the exploration, discovery, use and production of new molecules and materials to help solve the world's most urgent problems." Founded by Harvard University (Cambridge, Mass.; www.harvard.edu) researchers, Kebotix has developed "the world's first and biggest AI brain for chemistry and materials," which the company says can condense the research cycle for new molecules and materials from a decade to a period of months.

The Kebotix system, consisting of AI algorithms and robotics systems working in a reiterative closed loop, can rapidly and efficiently process enormous amounts of complex molecular data to discover new materials or generate new formulations of particular products with desired target properties, the company says.

In August 2020, Kebotix announced that it received $11.4 million in venture funding for its technology.

Another effort toward using AI and robotics in chemical discovery comes from IBM Corp. (Armonk, N.Y.; www.ibm.com). The company's European research arm has developed RoboRXN, which IBM Research Europe scientist and manager Teodoro Laino says is an example of bringing technology to bear in order to effect a large change in how synthetic chemistry is done. "Two things that have driven AI recently are image processing and natural language processing — algorithms that are capable of understanding grammar and words," says Laino. "There have been lots of recent improvements in this area."

Laino's team built a trained AI model that predicts chemical reactions and plans chemical syntheses by understanding hundreds of thousands of chemical reactions reported in the research literature. "By treating organic chemistry as a kind of language, we are able to provide an internet-connected, remote chemical laboratory driven by AI," he says.

To do that, the AI model translates chemical structures into textual representations, and transforms written descriptions of experimental procedures into protocols that can be executed by a laboratory robotic system (Figure 1). It can also predict reagents and solvents, as well as actions, such as add, stir, filter, extract, concentrate, and so on, so that a robot can carry out the synthesis of a given target. The RoboRXN system also can react to feedback from analytical instruments, such as high-performance liquid chromatography (HPLC), mass spectrometry (MS) and nuclear magnetic resonance (NMR), that can characterize reaction products.

The IBM project took an open approach with the chemistry community. Publicly released in 2018, IBM RXN for Chemistry is currently used by a community of 17,500 researchers who used the IBM AI predictive models more than 2.25 million times to predict reaction routes and perform reactions on the robotic system remotely, Laino says.

"The impact of the system will be felt in accelerating the discovery of new compounds and materials," Laino says, "as well as retaining knowledge from retiring chemists, and opening up new business for 'chemistry on demand.'" The IBM scientists are working to improve the AI's prediction of instructions, which is now 73% accuracy per step.

Laino and the IBM team envision the system as an accelerator for industrial chemistry, cutting the time for discovery of new industrially relevant chemicals, and shortening required development time.

Confined space inspections

Away from the R&D laboratory, robots are also gaining traction at plant sites. An attractive application area for the CPI is robotic inspections in areas that present safety hazards to humans, such as tanks, vessels, reactors and other confined spaces. Remote-operated robots for confined-space inspections is the objective of Invert Robotics Group Ltd. (Eindhoven, the Netherlands; www.invertrobotics.com), a company that has developed climbing robots capable of scanning the walls of tanks, vessels and reactors with a 30X optical zoom camera (Figure 2).

"The robots are platforms for a range of non-destructive testing (NDT) instruments," says Invert's U.S.

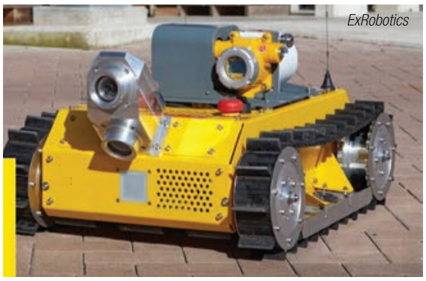


FIGURE 3. The robot shown here, from ExRobotics, can operate in potentially explosive or hazardous environments to assess incidents

Mitsubishi

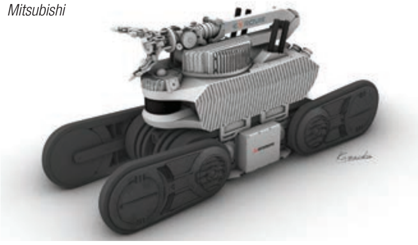


FIGURE 4. A prototype similar to the robot shown here can move autonomously through a refinery

sales manager Brent Bonner, such as ultrasonic testing for corrosion.

Two robot models use different mechanisms — vacuum suction and magnets — to hold onto vertical or inverted surfaces. One model features active sliding suction for smooth surfaces, such as stainless steel, aluminum and composites, while another model adds rare-earth-element permanent magnets that keep the robots on the surface of lined or coated surfaces for which suction is not effective. The robots have been used to inspect storage tanks, reactors, spray dryers and others, Bonner reports.

Hazardous environments

Robots are becoming the go-to technology for hazardous areas. ExRobotics B.V. (Delft, the Netherlands; www.exrobotics.global) has developed remote-controlled robots specifically for hazardous environments (Figure 3). ExRobotics has partnered with Yokogawa to offer the world's first robot with IECEx Zone 1 certification for commercial use. Known as ExR-1, this robot can be used to assess an incident at a CPI site before taking action, and to perform preventative maintenance by regular inspection rounds. Because data can be gathered more systematically, the need to have a human operator in the field is minimal, the company says.

ExRobotics was established in 2017 to commercialize robotics technology for use in potentially explosive atmospheres found at oil-and-gas production and processing facilities, which are often in remote locations with harsh environments. Equipment operating in these hazardous environments must adhere to IECEx Zone 1 requirements. The ExR-1 can be equipped with a range of sensors and cameras, has 4G LTE wireless network capabilities, and can be monitored and operated from a laptop, tablet or smartphone by an operator located in a safe control room anywhere in the world.

Users can realize safety improvements by having fewer people in hazardous locations, more cost-effective, frequent and reliable inspections of facilities; and reliable execu-

SMP Robotics

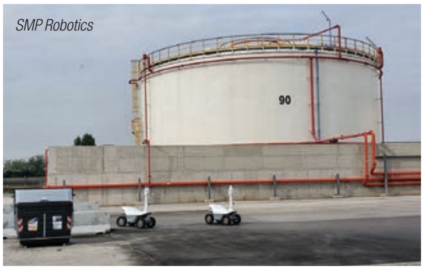


FIGURE 5. Working together, groups of autonomous robots, can provide plant security

tion of repeatable work processes, the company says.

Mitsubishi Heavy Industries, Ltd. (MHI; Tokyo, Japan; www.mhi.com) has also been pursuing an explosion-proof plant-inspection robot. MHI recently concluded an agreement with Eneos Corp. on joint development of a second-generation EX ROVR, a plant inspection robot with explosion-proof features to limit the danger of the robot igniting an explosion or fire from electric sparks or heat, even in areas with flammable gas. The agreement targets early realization of a practically viable model (Figure 4).

Last year, a prototype EX ROVR moved autonomously through several floors of an oil refinery and collected data through its various sensors, demonstrating its feasibility in the field. Under the newly agreed joint-development program, the companies will pursue greater volumes of high-quality onsite data through software improvements and the incorporation of a manipulator for photographing instrumentation from a directly facing position. Targets will also include enhancing usability.

Asset inspections

Another area where robotics is catching on is in the inspection of plant assets. An example comes from HEBI Robotics (Pittsburgh, Pa.; www.hebirobotics.com), a spin-off of Carnegie Mellon University's (CMU) Robotics Institute (www.ri.cmu.edu). The company recently announced that it is taking pre-orders for its MAPS (Modular Absolute Positioning System), part of a suite of robotic tools based on the articulated locomoting "snake robot" technology developed at CMU.

The MAPS system is designed for non-destructive testing (NDT) inspections of complex surfaces. It is a lightweight, portable, passive arm that continuously measures the full absolute position and orientation of a probe as it is moved along any surface. Thickness data from the probe is combined with positional data from MAPS to create fully-encoded scans of complex surfaces.

Manual fitness-for-service inspections can be used for many assets, but this approach lacks verifiability, HEBI says, because there is no practical way of measuring and encoding the inspection. Automated ultrasonic testing (AUT) systems enable the collection of encoded data, but are limited to simple surfaces, such as straight runs of piping, tank walls and plates. HEBI's MAPS system combines the flexibility of manual inspection with the robust data collection of AUT.

"The MAPS system can improve personnel safety by reducing the time spent by technicians in dangerous or confined areas because they can obtain NDT inspection data faster," says Bob Raida, COO of HEBI Robotics. Other advantages come in the realm of improving data quality, Raida says.

"Because scans are anchored to an absolute position in the world, it allows a confident alignment and comparison of multiple inspections over time. It removes the variability among different inspectors," he adds. The first deliveries of the system will occur in Q4 2020.

HEBI's long-term vision is to accelerate the incorporation of robots into industrial settings by developing robotics tools that can be used to solve problems by engineers who are not robotics experts. "We want to bring the power of robotics and automation development to the subject-matter experts at the plant sites," Raida says. Right now, robots are difficult to build because doing so involves a synergy of many engineering disciplines. If robots can become part of a 'toolbox' that is accessible to plant engineers, then they can build the robots to do what they need," he adds.

Quality control inspections

Robots can assist in applications where quality control is critical, such as in the manufacture of single-use medical devices, such as syringes, vials and catheters. All units must be visually inspected before being released for shipping, a function that has been done manually. Manual inspection poses several problems, because it can be difficult to find qualified employees, and worker can fatigue during a shift can alter decision making in inspections. This can negatively impact quality control.

In one example, robots from

FIGURE 6. Robotic tuggers can move raw materials and completed parts around a facility, reducing potential safety risks

Stäubli International AG (Pfäffikon, Switzerland; www.staubli.com) were employed to support automated inspection of medical catheters. In this application, molded catheters are dispensed into a vibratory feeder system, where they are oriented correctly and delivered into a servo escapement. The escapement separates eight catheters at a time for pickup by a servo transfer robotic arm. Two Stäubli TX2-60L six-axis robots handle the catheters after inspection, with high precision and while maintaining hygienic standards. The robot controller is integrated seamlessly into one programming platform.

After catheters are inspected for defects and noncompliance, the Stäubli robot picks the catheters off the transfer arm and separates those that failed inspection. The end-of-arm tooling on the robot features an eight-position gripper assembly that can individually select and release the catheter, as required. Control of the eight grippers is accomplished using a pneumatic manifold mounted directly on the arm of the robot. Each cell can inspect, sort and package over 50 catheters a minute.

Plant surveillance and security

Plant security and surveillance is another area in which autonomous robots have seen traction. For example, SMP Robotics Systems Corp. (Sausalito, Calif., www.smprobotics.com), offers fully autonomous, self-driving surveillance robots that are designed to navigate in a wide variety of weather conditions on any terrain in daylight or night. SMP Robotics service robots monitor security and safety of designated perimeters in fully autonomous mode. They conduct an inspection for gas leaks, air

quality issues, and equipment malfunctions, monitor and observe designated areas with 360-deg views using the advanced video monitoring system (VMS), infrared cameras and onboard sensors SMP Robotics says. The latest generation of outdoor robots are powered by artificial intelligence, deep learning, swarm intelligence technology, obstacle, behavior, and intruder recognition, as well as the state-of-the-art video surveillance system, allowing robots to step to service the open-air space at plant facilities, the company says.

Robots work as a team (Figure 5), covering large common areas simultaneously, redistributing routes (swarm intelligence) while always been connected with the dispatch center (ONVIF; a communications standard between a physical dispatch center and an autonomous device or system (camera, robot or sensor). Swarm intelligence is the collective behavior of decentralized, self-organized artificial systems, and arises out of a combination of technologies (including AI/deep learning and VMS) that work cohesively among more than one robot.

For example, after the robots are programmed to follow certain protocols and navigate the assigned route, swarm intelligence would help the robots rebalance the assigned route among themselves once a robot needs to recharge its battery, the company says. They would notify each other of any out-of-the-pattern behavior (including equipment failures, gas or oil leaks, electrical failures, air-quality issues and so on) as well as any obstacle occurrences (a fallen tree branch, garbage can, gate, and moving objects, including humans).

SMP Robotics robots are already deployed at user sites in more than 15 different countries around the globe. Clients include Eni Sp.A., Saudi Electric and Ejadah, in Dubai, among others.

Supply chain

Another application area for robotics in the CPI is in optimizing supply-chain efficiency. Inpro/Seal, a leading manufacturer of bearing isolators, recently announced the activation of robotic tuggers to improve product flow and advance lean manufacturing at its manufacturing facility in Rock Island, Ill. The Inpro/Seal facility will be using the robotic tuggers to move raw materials, in-progress parts and completed products around the facility, mitigating potential safety risks inherent in manual material handling, the company says (Figure 6). The system will also help reduce work-in-progress (WIP) and achieve lead-time reductions.

The adoption of the autonomous tuggers is part of a long-term manufacturing strategy at Inpro/Seal and its parent company, Dover Precision Components (Houston, Tex.; www.doverprecision.com), aiming to further improve safety, ensure quality, optimize productivity and quickly scale manufacturing volume in response to customer demand. From a safety perspective, the adoption of the tuggers reduces heavy lifting, pushing and tugging necessitated by human operation. From a lean-manufacturing perspective, the robotic tuggers eliminate waste associated with moving materials and parts, improve workflow and optimize lead time, the company says. ■

Scott Jenkins

Focus on Pumps

Netzsch Pumpen & Systeme

Schubert & Salzer Control Systems

Watson-Marlow Fluid Technology Group

Uraca

New sizes available for progressive-cavity pumps

NEMO progressive-cavity pumps with the FSIP design (photo) are capable of pumping and precisely dosing a large variety of different substances. The model is now available in stainless steel (photo) in the additional sizes NM053, NM090 and NM105, where only pumps in cast iron were available before. The FSIP concept is especially suitable for wear-intensive applications that require more service and maintenance work, because the design makes service work easy. The pump is designed so that the housing itself functions as a support and orientation guideline during maintenance, making sure each part "automatically" fits into its destination. Therefore, the change of all wear parts takes less than half of the time required previously. Constructed of stainless steel, the pump is suitable for media with temperatures up to 80°C and a pressure of up to 9 bars. — *Netzsch Pumpen & Systeme GmbH, Waldkraiburg, Germany*
www.netzsch.com

Cool and lubricate the pump shaft seal with this manifold

Centrifugal pumps depend on cooling and lubrication to operate efficiently, reliably and with a long service life. This company has developed an out-of-the-box solution for cooling and lubrication of the shaft seals in centrifugal pumps, in which the operating fluid is controlled via a compact manifold (photo). The adjustable angle-seat shut-off valve integrated into the block allows a flowrate of 10 to 50 L/h to be set. When the pump is started, the pneumatic valve opens simultaneously, so that cooling and lubrication are ensured immediately. — *Schubert & Salzer Control Systems GmbH, Ingolstadt, Germany*
www.schubert-salzer.com

Pumping shear-sensitive, viscous pharmaceuticals

The new Certa Plus pump series (photo) provides sustainable, high-quality, versatile fluid management for the pharmaceutical industry. Certa Plus is an innovative advancement over conventional lobe pumps, offering pharmaceutical manufacturers lower shear, lower power consumption, full traceability and ultimate cleanability when transferring syrups, oils, creams and gels. Certa Plus was developed to guarantee cleanliness, with added capabilities that assure quality across a wide range of pharmaceutical products. The efficient design of the pump not only reduces cleaning time but also saves electricity, minimizing cost and carbon footprint. The pump is said to require up to 50% less power than lobe or circumferential piston pumps. — *Watson-Marlow Fluid Technology Group, Falmouth, U.K.*
www.wmftg.com

High-temperature applications for plunger pumps

This company designs and manufactures high-pressure plunger pumps (photo) and units for operating pressures up to 3,000 bars (43,500 psi), with driving powers up to 2,600 kW (3,500 h.p.). One area where such pumps are used is in petroleum refining. For example, various procedures can be used to process residual oil, which is accrued after refining heavy oil, bitumen or normal crude oil. It is then compressed to around 150–250 bars, mixed with H_2 and fed into the hydrogenation reactor at up to 450°C. This critical process uses pure H_2, so system failure, particularly in the feed pumps, is not acceptable. Otherwise, extremely critical operating conditions may arise. As a result, redundant solutions with standby capacity for the pumps are usually used. When in use, each pump is also monitored with adapted instrumentation to detect possible faults early and react to them accordingly, so that hazardous situations do not occur. — *Uraca GmbH & Co. KG, Bad Urach, Germany*
www.uraca.com

A corrosion-resistant gear pump that is quick to clean

This company recently introduced the new, patented FQ series pump (photo, p. 17) to its flexinox corro-

sion-resistant gear pumps. This FQ quick cleaning version is being released for applications that require the transfer line to be cleaned and washed at the end of each production batch. The pump can be disassembled quickly, without having to dismantle the drive shaft from the drive motor and the seal. This feature can be applied also on the existing pump series (CX, TX, FX, DX) by using the FQ kit, or the pump can be selected as a FQ model itself. The FQ kit provides high flexibility and functionality with easy maintenance and part replacement possibilities. — *Maag Group, Oberglatt, Switzerland*
www.maag.com

Horizontal close-coupled, vortex end-suction pumps

The Series 1600 horizontal close-coupled, vortex end-suction pumps (photo) have a wide range of applications, including food-processing solids, wastewater treatment, pollution control, slurries and solids. The Series 1600 has capacities up to 1,600 gal/min, heads up to 170 ft TDH, and handle temperatures to 250°F. These pumps are designed with a variety of materials of construction, such as cast iron, 316 stainless-steel fitted, all 316 stainless steel, alloy 20 or CD4MCu. Additionally, the pumps are designed with a convenient back pull-out cost-saving feature to allow for easy inspection or service and maintenance without disturbing the piping to the pump. The impeller has a fully recessed design, which accommodates passage of solids. All impellers have wiping vanes, which reduce axial loading and prevent dirt from entering the sealing area. — *Vertiflo Pump Company, Blue Ash, Ohio*
www.vertiflopump.com

This submersible pump is hermetically sealed

The self-regulating submersible pump MPCTAN (photo) prevents the seal from coming into contact with the product due to its vertical design. The hermetically sealed pump also features a sophisticated safety concept: the impeller back vanes guarantee a complete hydrodynamic seal. Gas barriers (sealing gas) protect the bearing unit against the penetration of product vapors. Bearing and sealing units run without product contact. The dry-running magnetic coupling has no contact with the pumped liquid or its gases. Possible faults in the bearing, seals or separating can are reliably tracked by the sealing gas monitoring system. The MPCTAN submersible pump is thus approved for the highest hazard zone 0 (ATEX). The proven pump now has an immersion length of up to 5.5 m for high-temperature applications, such as in molten salt. — *Paul Bungartz GmbH & Co. KG, Düsseldorf, Germany*
www.bungartz.de

A stainless-steel AODD pump for industrial applications

The new ADX Series stainless-steel air-operated double-diaphragm (AODD) pump (photo) was developed to replace legacy Chemicor AD Series pumps. The ADX Series incorporates an array of design enhancements that provide simplified maintenance, improved cleaning and increased safety, says the manufacturer. Features include easy start-up, rotating suction and discharge ports, gentle displacement, dry-running and self-priming operation, no diaphragm discs, and the company's patented maintenance-free Perswing P air control system. — *Almatec, Duisburg, Germany*
www.almatec.de

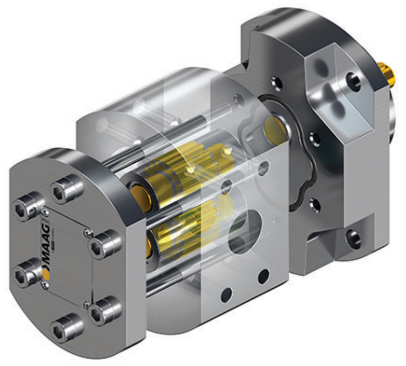
This aseptic pump performs two duties

The LKH Prime 10 UltraPure self-priming pump (photo) is said to be the most compact ever in the LKH self-priming pump range. Suitable for duties up to 35 m^3/h, it is primarily engineered for cleaning-in-place (CIP) return, but also transfers product in sterile processes. This delivers savings of up to 50% in capital expenditures and installation, and 30% in annual operating expenses, says the company. Other advantages include: up to 60% more energy savings than liquid-ring pumps and up to 25% more than other airscrew pumps. — *Alfa Laval AB, Lund, Sweden*
www.alfalaval.com

Sliding-vane magnetic-drive pumps

Magnes Series pumps (photo, p. 18) are positive-displacement rotary-vane pumps that use a magnetic drive with-

Maag Group



Vertiflo Pump Company

Paul Bungartz

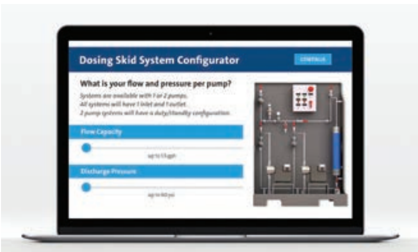
Almatec

Alfa Laval

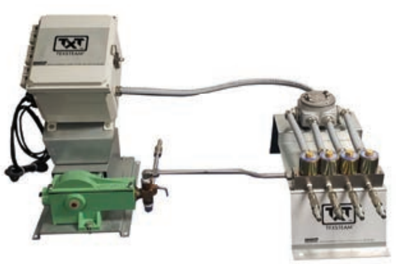
Blackmer

KNF Neuberger

Leybold



Grundfos



Dresser NGS

out dynamic seals, providing leak-free pumping for difficult-to-seal, expensive, valuable, dangerous and hazardous liquids. With this rotary-vane magnetic-drive pump design, these pumps combine the leak-free benefits of a magnetic-drive pump with the numerous advantages of sliding-vane technology, including self-priming, line-stripping, product recovery, indefinite dry-run capability, solids handling, and more. The pumps are available in a 3-in. model (a 4-in. model will be available in January 2021) in both ductile iron and stainless-steel construction — *Blackmer, part of PSG, a Dover company, Grand Rapids, Mich.*
www.blackmer.com

Introducing four new vacuum/compressor pumps

The new N 630 diaphragm vacuum/compressor pump series (photo) delivers high pressure and gas tightness with a durable, long-life design. Four versions are available for use in industrial coolant systems, gas recycling, gas and emissions measurement and analysis and leak detection across a wide variety of industries. The pumps have a long service life and generate vacuum down to 0.74 in. Hg (25 mbar abs), positive pressure up to 174 psig (12 bars rel.), and deliver a flowrate up to 2.4 ft^3/min (68 L/min). The cost-efficient and reliable diaphragm gas pumps are available in four variants: either one- or two-headed and connected in series or parallel, as a vacuum pump, or as a compressor. All models come with long-lasting EPDM or chemically resistant PTFE-coated diaphragms for exceptional durability and service life. — *KNF Neuberger, Inc., Trenton, N.J.*
www.knf.com/en/us

Two new compact vacuum pumps that are energy-efficient

This company has expanded its Ecodry plus product family of dry, multi-stage Roots vacuum pumps for laboratory, research and development and analytical applications. The current Ecodry 40 and 65 plus models are now joined by the new, smaller pump sizes Ecodry 25 and 35 plus. This completes the company's range of quiet, low-maintenance and economical fore-vacuum pumps and fills the gap between Scrollvac 18 plus and Ecodry 40 plus. Thanks to technical optimizations, the vacuum pumps are smaller and more energy-efficient than competitive products, says the company. The oil-free multistage Roots pumps Ecodry 25 and 35 plus also have a maintenance interval of five years, during which time they run without any servicing. — *Leybold GmbH, Cologne, Germany*
www.leybold.com

A digital tool for configuring a dosing system

The Dosing Skid Configurator (photo) is an interactive digital tool featuring thousands of configuration variants to serve an array of applications with complete chemical dosing solutions. By answering a few simple way-of-use questions to configure the best solution, the Dosing Skid Configurator generates an interactive 3-D model of a pre-engineered dosing skid system — one of 16,000 possible configuration variants — a materials list, dimension drawings, list pricing, a downloadable submittal package and a contact form to reach a distributor to learn about ordering and availability. Potential applications include dosing skid systems for water treatment, peracetic acid (PAA) dosing for food and beverage facilities, and so on. — *Grundfos, Bjerringbro, Denmark*
www.grundfos.com

Inject up to four wellheads with a single pump

This company has launched a multipoint injection controller adjustment for its Texsteam pumps (photo). Texsteam multipoint injection will be used in oil-and-gas wellhead chemical-injection operations to distribute chemicals from a single chemical-injection pump to multiple injection points. This lowers capital spend by reducing the amount of equipment required for chemical injection. Instead of needing four pumps for four different wellheads, the operator will now be able to inject four wellheads with just one pump, says the company. The Texsteam multipoint injection system works up to a maximum operating pressure of 2,500 psi, with the solenoid assembly requiring only 10 W of power consumption. — *Dresser Natural Gas Solutions (Dresser NGS), Houston*
www.dresserngs.com

Gerald Ondrey

New Products

Reduce costs with this transmitter-style GC

The Rosemount 700XA gas chromatograph (GC; photo) is said to be the industry's first single-analyzer solution for measuring both sulfur compounds and the energy content of natural gas. The 700XA is a cost-effective approach to meet gas-quality and heating-value requirements for pipeline distribution, processing of liquified natural gas (LNG), mixed and high-purity natural gas liquids (NGLs), as well as international LNG commerce. The 700XA is equipped with a micro flame-photometric detector (FPD), which enables users to reduce initial equipment cost by as much as 50% and footprint requirements by up to 40%, says the company. — *Emerson Automation Solutions, Shakopee, Minn.*
www.emerson.com

Introducing a new range of bellows seal valves

This company has expanded its product line to include a range of bellows seal valves, including the BSA (photo) and A3S isolation valves. These valves are engineered to maintain plant safety and save energy by totally eliminating stem seal leaks, which will help oil, gas, petrochemical, pharmaceutical, food and beverage manufacturers save energy and ensure operator and plant safety, says the company. The BSA valve range is a flexible, user-friendly isolation solution that includes a throttling plug that allows manual regulation to adjust line pressure and flow. It can also be used as a basic control valve or a substitute for "bypass" lines. The high-integrity A3S bellows sealed valve is suitable for use under higher-pressure steam, gas and liquid applications, since it is designed to ASME Class 800. — *Spirax Sarco, Inc., Blythewood, S.C.*
www.spiraxsarco.com/us

New controllers for radar transmitters

The new Sitrans LT500 level, flow and pump controllers (photo) are suitable for radar and ultrasonic transmitters or any other two-wire 4–20-mA devices. From basic level control to complex pumping routines, these instruments deliver the accuracy and reliability demanded by a variety of applications. Complete with up to two measuring points, six control or alarm relays, two discrete inputs, three analog outputs and communications options, Sitrans LT500 is an attractive option for controller applications. Users can easily retrofit older equipment with Sitrans LT500, as improved system control delivers savings directly to a company's bottom line. By scheduling pumps before high-demand periods begin, users can avoid peak energy hours and the increased prices that accompany them. — *Siemens AG, Munich, Germany*
www.siemens.com

Monitor and configure networks intuitively with these switches

IT specialists rarely perform the implementation, commissioning and maintenance of Ethernet installations, so this company is introducing its Lean-Managed Switches (photo) for secure and robust network installations, as well as for ensuring high availability and security. The new switches are available with 8 or 16 copper ports capable of baud rates up to 1,000 Mbit/s. Devices with two extra SFP slots (100/1,000 Mbit/s) are available as an option for connecting fiber optic cables. A Power over Ethernet (PoE) version supplies connected PoE devices with 24 V d.c., which is common in control cabinets. The power output per PoE port can be up to 30W. The Web-Based Management allows installation, commissioning and diagnostics to be performed without extensive IT knowledge. — *WAGO Kontakttechnik GmbH & Co. KG, Minden, Germany*
www.wago.com

New mill-discharge pumps for efficient slurry handling

This company's mill-discharge (MD) pumps (photo, p. 20) are robust and have been designed to operate reliably in highly abrasive environments, providing optimal solutions for each part of the concentrator plants of a minerals-processing facility. The MD pumps have been designed for efficient operation and longest wear life to match the mill's uptime. An oversized robust steel shaft and

Emerson Automation Solutions

Spirax Sarco

Siemens

WAGO Kontakttechnik

Metso Outotec

Phoenix Contact

Endress+Hauser

Spectro Analytical Instruments

extra thick casings and liners are just some of the heavy-duty components that are equipped with the MD Series pumps. The pumps are available in two tailored solutions, MDM and MDR. They cover flows of up to 12,000 m^3/h, with inlet sizes ranging from 250 to 700 mm, with either metal (MDM) or rubber (MDR) lining. Both pump types offer excellent resistance to abrasion and erosion and are suited for heavy-duty use. — *Metso Outotec Corp, Helsinki, Finland*
www.mogroup.com

A compact computer for entry-level IIoT applications

The BL2 BPC 1500 (photo) is a compact industrial PC (IPC) for rugged environments with limited space. This box IPC is designed for entry-level automation, small machine control and industrial internet of things (IIoT) applications, such as edge or fog computing or decentralized data collection and processing. With its fanless design, solid-state mass storage and heavy-duty metal housing, the BL2 BPC 1500 can operate in demanding industrial applications. Additional standard features include 32-GB eMMC internal mass storage, 12 to 30 V d.c. wide-voltage operation and DIN rail mounting. — *Phoenix Contact Inc., Middletown, Pa*.
www.phoenixcontact.com

A new generation of thermal mass flowmeters

The new Proline t-mass F/I 300/500 thermal mass flowmeters (photo) are reliable and versatile for measuring pure gases and gas mixtures, and each has numerous alarm functions, as well as bidirectional measurement capability and reverse flow detection. The flowmeters are suitable for compressed air, natural gas, protective gas or oxygen. The meter has an all-metal sensor design and unique monitoring functionality. Even when process and ambient conditions significantly fluctuate, t-mass ensures high measurement accuracy (±1.0%) with excellent repeatability (±0.25%). Gas flows with low pressure and a low flow velocity can also be measured easily thanks to a high turndown ratio. t-mass F and I can operate at process temperatures up to 356°F and pressures up to 580 psi. — *Endress+Hauser, Greenwood, Ind.*
w**ww.us.endress.com**

New multigas detector measures in low-ppb range

The focus of the X-act 7000, in combination with the MicroTubes for different gases and vapors, is to measure carcinogenic and toxic substances in the lower parts-per-billion (ppb) range. The range of gases to be measured is being constantly expanded. The measurement-sensitive system of the X-act 7000 is based on colorimetric chemical-sensor technology and measures even the lowest ppb concentrations. It can replace conventional laboratory analysis and delivers exact, reliable results directly on site. False-positive measurement results and false alarms can be largely reduced. This saves time and costs. The RFID tags applied to the MicroTubes contain all the calibration data that are valid for the typical period of use of one year. Complex functional tests and manual calibration procedures are no longer necessary. All possible temperature and humidity influences are already taken into account during factory calibration. The analyzer is explosion-proof and certified in accordance with ATEX/IECEx for zone 0 and CSA Class I, Zone 0. — *Dräger Safety AG & Co. KGaA, Hamburg, Germany*
www.draeger.com

Analyzer's interface delivers high sensitivity for trace elements

The newest version of the Spectrogreen inductively coupled plasma, optical emission spectrometry (ICP-OES) analyzer (photo) features this company's proven twin interface (TI). The TI automatically combines both axial and radial plasma views — looking both across the plasma and from end-to-end — optimizing sensitivity, linearity and dynamic range while avoiding matrix effects, like easily ionizable elements (EIE). The Spectrogreen TI is the third and newest version of this family of ICP-OES analyzers. It delivers numerous advantages for a wide array of routine laboratory analyses. — *Spectro Analytical Instruments GmbH, Kleve, Germany*
www.spectro.com ■

Gerald Ondrey

Hydrogen flame hazards and leak detection

Department Editor: Scott Jenkins

The use of molecular hydrogen is common across the chemical process industries (CPI). Annually, 70 million metric tons of H_2 are produced worldwide. Most industrial H_2 production currently occurs via steam reforming of methane, but production via water electrolysis is growing. This one-page reference provides information on H_2 flame hazards and leak detection. Tables 1 and 2 outline major industrial uses of H_2 and its key properties, respectively.

TABLE 1. MAJOR INDUSTRIAL USES OF HYDROGEN [*1–3*]

Industry sector	Uses of H_2
Metals	In steel manufacturing, H_2 is used, along with inert gases, to establish a reducing atmosphere. This is required for heat treating steel and welding. H_2 is used in annealing stainless-steel alloys, sintering and copper brazing
Petroleum refining	• In petroleum refining, H_2 is used to hydrogenate hydrocarbons to improve combustion characteristics of fuels. H_2 is catalytically combined with intermediate streams to convert heavier, unsaturated compounds to lighter and more stable compounds • H_2 is also used to remove sulfur from crude oil fractions
Pharmaceuticals	H_2 is used in the manufacture of pharmaceutical products, such as in asymmetric catalytic hydrogenation reactions to create chiral centers
Chemicals	H_2 is used as a raw material in the chemical synthesis of ammonia (Haber-Bosch synthesis), methanol, hydrogen peroxide, polymers and organic solvents
Glass and ceramics	In float glass manufacturing, panes of glass are made by depositing molten glass onto a tin bath to obtain a smooth surface. H_2 (with nitrogen) is used to create a positive-pressure atmosphere to prevent oxidation of the tin bath
Food and beverage	H_2 is used to hydrogenate unsaturated fatty acids in animal and vegetable oils, producing solid fats for margarine and other food products
Electronics	H_2 can be a carrier gas for active trace elements in the manufacture of semi-conducting layers in integrated circuits
Miscellaneous	• Power-plant generators can be cooled with H_2, since it offers low frictional resistance and high thermal conductivity • Liquid H_2 is used as a rocket fuel in the space industry • H_2 is used as a protective atmosphere in the fabrication of nuclear fuel rods

Hydrogen flammability

Although H_2 is nontoxic, it is highly flammable and explosive. The National Fire Protection Association (NFPA; Quincy, Mass.; www.nfpa.org) rates H_2 as a "4" on the flammability scale (the highest rating), because H_2 is flammable when mixed with air, even in small amounts, and the minimum ignition energy (MIE) is small (0.019 mJ for a gas-air mixture). Hydrogen can also self-ignite without energy from an external source when it is leaking from a pipe at high pressure.

Hydrocarbon flames differ from H_2 flames. A H_2 flame emits low levels of infrared radiation and visible light, so it will not give off intense heat and light. Therefore, it cannot be easily detected by human senses. It is difficult to see a H_2 flame even up close. Plant workers may see a shimmering, mirage-like area or possibly sparks, which are actually dust particles burning briefly in the flame [2].

TABLE 2. SELECTED PROPERTIES OF HYDROGEN GAS [*1,4*]

Property	U.S. Units	SI Units
Chemical formula	H_2	H_2
Molecular weight	2.016 g/mol	2.016 g/mol
Boiling point at atmospheric pressure	–423°F	–252.8°C
Density of gas at boiling point	4.23 lb/ft^3	67.76 kg/m^3
Melting point	–434°F	–259.2°C
Latent heat of vaporization (at boiling)	191.7 Btu/lb	446.0 kJ/kg
Specific gravity of H_2 at 1 atm (air = 1)	0.0696	0.0696
NFPA ratings	Health = 0 Flammability = 4 Instability = 0	n/a
Flammable limits in air	4% to 75%*	n/a
Autoignition temperature	752°F	400°C
Department of Transportation Hazardous classification scheme label code	2.1 (flammable gas)	

*Flammable limits are the lower volume limit concentration of a chemical in air that will continue to propagate a flame once initiated. The flame would propagate at any concentration from the lower limit until it reaches an upper limit where the fuel to air ratio is too rich and the flame is quenched.

H_2 leak detection

Gas detection equipment can sense a H_2 leak before it ignites, increasing the possibility of stopping a leak before it causes a fire or explosion. Catalytic bead (Pellistor) detectors sense H_2 in combustible concentrations when it combines with oxygen to produce heat. This sensor usually consists of a matched pair of platinum wire-wound resistors, one of which is encased in a ceramic bead. The active catalytic bead is coated with a catalyst, while the reference catalytic bead remains untreated. The resistors are then enclosed behind a flame-proof sinter or porous filter. When the combustible gas comes in contact with the active catalytic bead surface, the gas is oxidized and heat is released, which changes the resistance of the wire. The reference (passive) bead maintains the same electrical resistance in clean air as the active bead, but does not catalyze combustible gas. Combustible gas concentrations are then determined by comparing the difference between the active and passive bead circuits. Limitations include the susceptibility to poisoning of the catalytic beads and their inability to signal a fault when they fail [2].

Hydrogen quickly floats upward and disperses, so detectors should be located close to and above spots where a leak might occur (just above a valve, for example).

Multi-spectrum NIR

If a flame ignites, multi-spectrum infrared (MIR) flame detection has become the preferred choice for detecting H_2 flames in industrial settings. Some MIR detectors are designed specifically to detect the IR radiation from H_2 flames. MIR flame detectors rely on a combination of IR filters and software analysis to detect flames and reduce the potential for false alarms. ■

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Isopropyl Alcohol Production from Acetone

By Intratec Solutions

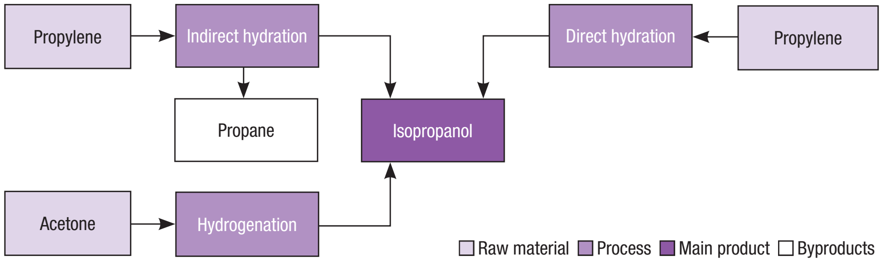

FIGURE 2. Isopropanol production can occur via different pathways, as shown here

Isopropyl alcohol (isopropanol or 2-propanol) is a colorless and flammable liquid with a strong odor. Isopropyl alcohol was among the first petrochemical products to be industrially manufactured — it has been produced since 1920. At that time, isopropanol was generated through the indirect hydration of propylene, a process that uses sulfuric acid to react with propylene and generate a compound that will react with water to produce isopropanol. Today, isopropanol is one of the most produced C1 to C5 alcohols, ranking third in commercial production, behind methanol and ethanol.

The main industrial applications of isopropyl alcohol are as a chemical intermediate and as a solvent in the manufacturing of cements, primers, paints, varnishes, skin cleaners, perfumes, lotions, shampoos and deodorants. It is also used as a disinfectant and antiseptic.

The process

The present analysis discusses an industrial process for isopropanol production. The process under analysis comprises two main sections: (1) reaction; and (2) purification (Figure 1).

Reaction. Hydrogen is compressed and fed, along with liquid acetone, to the upper part of a circulation reactor. The circulating mixture passes through a gas-liquid separation vessel. Part of the liquid is cooled — removing the heat generated by the exothermic reaction — and recycled to the reactor. The remainder is cooled and routed to a second reactor, followed by a second vapor-liquid separation stage. The liquid portion obtained after the second vapor-liquid separation is sent to the purification stage. The vapor portion is mixed with the vapors from the first gas-liquid separation and also sent to purification.

Purification. In the purification stage, the vapors from the reaction are fed to a condenser, where isopropanol and acetone are recovered. Most of the uncondensed vapors are recycled to the hydrogen compressors. The remaining portion of the hydrogen-rich gaseous stream, the condensate from the condenser and the liquid product from the reaction are fed to a deaeration tank to remove any gases dissolved in the crude liquid product. The crude product is then subjected to dehydration by means of molecular sieves, and finally fed into a purification column, from which purified isopropanol product is withdrawn as a side stream. Low-boiling components are separated as the column's overheads product, while high-boiling impurities are obtained as the bottoms product.

Production pathways

The main raw materials for isopropanol manufacture are propylene and acetone. Propylene is reacted with water directly, or indirectly (in the presence of sulfuric acid), to form isopropanol. Acetone, in turn, passes though a hydrogenation process. Figure 2 presents different pathways for isopropanol production.

Economic performance

The total operating cost (raw materials, utilities, fixed costs and depreciation costs) estimated to produce isopropanol was about $1,000 per ton of isopropanol in the fourth quarter of 2016. The analysis was based on a plant constructed in the U.S. with capacity to produce 60,000 metric ton per year of isopropyl alcohol.

This column is based on "Isopropyl Alcohol Production from Acetone – Cost Analysis," a report published by Intratec. It can be found at: www.intratec.us/analysis/isopropyl-alcohol-production-cost. ■

Edited by Scott Jenkins

Editor's note: The content for this column is supplied by Intratec Solutions LLC (Houston; www.intratec.us) and edited by *Chemical Engineering*. The analyses and models presented are prepared on the basis of publicly available and non-confidential information. The content represents the opinions of Intratec only. More information about the methodology for preparing analysis can be found, along with terms of use, at www.intratec.us/che.

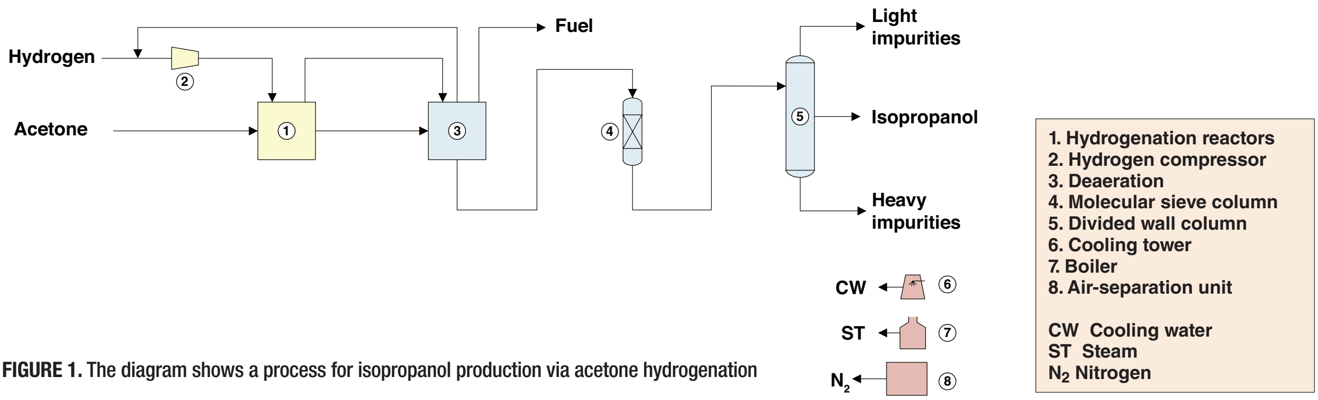

FIGURE 1. The diagram shows a process for isopropanol production via acetone hydrogenation

Part 1

Bio-based Processing Best Practices

Development of robust bio-based processes will be key to accelerating the transition to a circular economy, and there are many economic and technical considerations that will help companies experience success with bio-based innovations

Gert-Jan Gruter
Avantium

It is no secret that the clock is ticking for companies in all sectors to meet environmental sustainability targets. With the world coming together to forge a more renewable economy, heads are turning to bio-based products and bioprocessing technologies for response and resolution. But in a market where innovation is the key to success, how can stakeholders at all levels ensure that new technologies are bringing real value?

Unlocking an understanding of best practices in bio-based products and processes will provide answers. However, this requires a number of factors to be considered deeply, including true insight into the drivers of change, strategic thought with regard to commercialization and an awareness of how mindsets must be adapted to respond to current climate needs. Environmental experts in the cutting-edge bio-based processing industry must be carefully enacting these best practices — as well as educating the world around them — so that well-meaning brands and consumers can make sure that they are truly investing in technologies and innovations that can accelerate the supply chain successfully toward a tangible, sustainable future.

Market drivers: Who holds the power?

It all starts with an understanding of market drivers. This will allow companies within the bio-based processing sector to deliver real value with the technology and the products they develop. Modern-day consumers are becoming more and more active in their demand for sustainability in all aspects of their lives, and are the main reason why brands are beginning to look for sustainable options. Previously, large consumer-facing brands contextualized their refusal to shift toward sustainable measures by claiming that it was too expensive and that consumers were not willing to pay for it. However, as many industrial sectors are learning now, this simply is not the case.

FIGURE 1. Studies have shown that customers will pay more for products that present a sustainable alternative to conventional materials, but manufacturers must be prudent in their selection of raw materials and end-use applications

Results of a recent investigation [*1*] into the so-called "Green Premium" showed that consumers are driven to pay more for goods that they know are sustainable, with almost three-quarters of respondents stating they would be prepared to pay more for a proven sustainable package (Figure 1). Interestingly, according to the study, this behavior is partially motivated by guilt. Conversely, the study also found that there was a motivation from consumers who want to feel good about using brands that are clearly environmentally friendly. This phenomenon is known by the term "Seen to be Green" and is also driving consumers to pay a premium for sustainable products.

Understanding this key driver for mass-market bio-based processing allows a business to tailor products to market needs. Consumers want products and

technologies that make a positive impact on the world around them and also allow them to be visible about their support for sustainable measures. Correctly approaching this aspect of consumer demand is essential when it comes to commercialization of bio-based processes and technologies.

FIGURE 2. Deployment of an intermediate-scale pilot plant is a crucial, and often difficult, step between the initial demonstration of a new bio-based technology and reaching full commercialization

Commercialization

It is clear that there is an appetite for sustainable goods, but even with a strong vision for technology, those in the industry still need to navigate the waters of commercialization. It is prudent to realize that bio-based feedstock is currently the main alternative for fossil feedstocks to produce plastic materials. New technologies can take a very long time to scale up, and most bio-based technologies are currently at a relatively early stage. In fact, it was recently reported that less than 1% of the 350 million tons of plastics produced annually is currently bio-based [*2*].

Those in the bio-based processing industry have to plan the steps in between the demonstration stage of technology and full commercial scale — this is the stepping-stone toward being cost competitive, and is often the biggest hurdle in developing new technologies for bio-based processing (Figure 2).

Here, focusing on market needs is essential. For instance, trying to position a new bio-based material as a "green" version of a commoditized product, such as polyethylene terephthalate (PET), places great pressure on the new product in terms of price and volume. Due to these factors, it may be smart to initially limit a new material to an area where it can bring a unique benefit. High-performing bio-based technologies will employ a focused strategy, for instance targeting demanding packaging solutions for high-value applications, such as carbonated beverages, alcoholic beverages and fruit juice. Market experience and lower prices at larger production scales can then be used to expand into larger volumes at the right time.

Generally, it is always best to give the market something new. If you are simply offering a product where the performance is the same as what you hope to replace, then you have to compete on price right from the outset. It may seem like there is space in the market for commercial bio-based polyethylene, but when you look at the properties for such a material, it is similar to its fossil-based counterpart. This means differentiation can only happen through price, since the performance is the same. This is a trap all innovators should avoid falling into, unless they make sure to use the feedstock in the best possible way. Turning sugar into ethylene (via ethanol) requires at best 3.5 tons of sugar per ton of ethylene, as most of the mass (all of the oxygen) of the sugar is lost to CO_2 and water in this process. Whereas converting sugar to ethylene glycol has a much better ratio of, at best, 1 ton of sugar per 1 ton of ethylene glycol, since all of the sugar's mass is retained in the product. This is an example of a drop-in (meaning that the bio-based alternative is essentially identical to the incumbent material) bio-based product that makes perfect sense. Companies that produce ethylene glycol and are looking to expand production volumes would be drawn to this technology when purchasing assets to meet consumer demand. In such cases, this kind of drop-in technology is perfect for phasing out older, less economically and less environmentally friendly processes.

It is believed that plastic packaging production is expected to quadruple by the year 2050 [*3*], so moving for-

ward, the industry should be focused on making sure that demand is met with alternative sustainable solutions. When companies are building new assets to handle the strain of this increasing demand, they are in a better position if the products they are producing are sustainable, cost-competitive and high-performing, all while meeting consumer demands. This is where new bio-based products and bioprocessing technologies can provide great value, and these factors should certainly be at the forefront even during early conceptual work related to new bio-based processes.

FIGURE 3. Forestry waste residue is one example of a feedstock source that provides a more circular solution for the production of new bio-based materials

Bringing real value

A bio-based product or technology needs to do more than sell well, it needs to bring real environmental value to not only the industry, but to society as a whole. Consumers are educating themselves on environmental science more than ever before. However, there is still a great deal of confusion in some areas. This can make balancing consumer satisfaction with environmental value tricky.

Consumers often get fixated on the idea of biodegradability, thinking that perhaps a plastic that "returns to nature" is more environmentally friendly. While it is true that biodegradability is

a concern, and improving this property would certainly help to combat plastic accumulation, collecting plastics with the goal of biodegrading them possesses an amount of flawed logic. Not only does biodegradation do nothing to cushion feedstock, but this process simply turns a polymer into CO_2 — which is released into the atmosphere — and has no fertilizer or compost value.

To achieve the best of both worlds, the goal should be to create a plastic that is designed for recycling, which creates a circular economy of carbon, but which can also biodegrade in an acceptable time period if the product ends up in nature through what can be likened to "human error."

In terms of product performance, it is key that biodegradation does not take place during normal use of a plastic — you only want this process to begin when it is exposed to the presence of composting bacteria and fungi.

To ensure this balance between recyclability and biodegradability, best practices would recommend the use of biodegradation analysis to test if products designed for packaging are "safe in nature." In terms of biodegradability, products should be tested under both industrial composting conditions (air/oxygen at 58°C in soil) and under ambient conditions. The former of these should take around a year, but the latter can take several years. A long-term commitment to understanding the lifecycle of new technologies is extremely important, and this kind of analysis is vital to providing the industry with effective innovation.

When developing drop-in products that are chemically identical to fossil-based counterparts, end-of-life and use-phase analysis may not be relevant in all cases. Regardless of this, it is always vital to consider the impact on the environment that the production phase of a technology has. The lifecycle phases themselves consist of several smaller steps that include the extraction of the raw material, intermediate products and final manufacturing, which all count within the production phase. The impact assessment should also consider the energy consumption and resource depletion, as well as the effect of output emissions and waste on environmental concerns, such as climate change, summer smog, acidification and eutrophication (harmfully excessive nutrient content in bodies of water).

Currently, one of the great opportunities to be realized with bio-based processing is to define the feedstock that will be used as the gold standard. As an example, consider sugar as a replacement for petroleum. The polyolefins polyethylene, polypropylene and polystyrene, currently made from petroleum, do not contain oxygen, and so they are therefore not very logical polymers to make from sugars, where more than 50% of the molecular weight is oxygen. By focusing on glucose as a feedstock, the industry is driven to make materials that are better suited to a biomass feedstock, such as polyesters, polyamides and polyurethanes, which have better (closed-loop) recyclability, and in many cases, also better biodegradability than polyolefins. These novel bio-based plastics are designed for reusing and recycling, and to be "safe in nature" — where they degrade in a few years, rather than hundreds of years.

Glucose can be used sustainably as a feedstock by utilizing glucose from sources where it would normally be a waste product, such as forestry residue (Figure 3). This approach to industry waste is key to realizing a circular future.

In the future, industry can target one of the worst offenders when it comes to waste with the same philosophy — CO_2. A new area of technology, carbon capture, utilization and storage (CCUS) brings the potential to harness CO_2 — the largest contributor to global warming — either from the air or directly from industrial processes. When paired with an electrocatalytic platform, CO_2 emissions can be used as a feedstock to develop high-value chemicals (and eventually liquid fuels for aviation and other end uses) to replace products previously made from fossil-based feedstocks. This would allow companies to offset their CO_2 emissions and feed this waste product directly back into the industry to fuel different product streams.

An inspiring time

As governments impose more regulations on single-use plastics and the industry follows this transition from fossil to biomass feedstocks, we expect to see more innovation in the products we produce, with more exciting and surprising properties. These properties, coupled with dedicated lifecycle analysis, are the keys to commercializing effective technologies and increasing the demand for them.

We are truly beginning to see an uptick of bio-based processing for chemicals and polymers. However, leaders in the industry need to make sure that they are adopting best practices to drive successfully toward a sustainable future. It is the industry's job to educate consumers and help them to use the power they have over brands to create a positive impact on the world, as ultimately it is their influence that will truly accelerate the transition to a fossil-free world. ■

Edited by Mary Page Bailey

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Author

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Part 2

Separations are Key to Bioprocessing Success

Choosing an optimal separation technology and associated equipment is essential in all types of bioprocessing applications

Thomas Raiser and Ramnik Singh
Sulzer Chemtech

IN BRIEF

NEXT-GENERATION BIOFUELS

MAXIMIZING CARBON CAPTURE

CHOOSING A SEPARATION METHOD

DEFINING THE UNIT DESIGN

CONTINUOUS IMPROVEMENT

Recent advances in bioprocessing and bio-based products are bringing unprecedented innovations to the manufacturing sector, offering businesses the potential to unlock new, sustainable market opportunities. Key examples include leveraging economical and more sustainable raw materials or turning waste into useful products, thus benefitting the environment while helping businesses to tap into additional revenue streams. Utilizing reliable, high-performance mass-transfer and separation technologies is essential to fully benefit from bioprocessing methods.

Already well-established in many industrial sectors, such as life sciences and food and beverage, bioprocessing can also prove advantageous to a wider range of industries. It offers a unique way to implement sustainable carbon-capture strategies, as well as to utilize resources that are inaccessible with conventional processing methods.

Perhaps the clearest example is provided by an extremely popular process, microbial fermentation, which is used to produce fuels and chemicals from carbon-rich materials — the most common feedstock being carbohydrates from plant-based resources that characterize first- and second-generation biorefineries (Figure 1).

More precisely, bioethanol facilities use agricultural crops, herbaceous plants or lignocellulosic biomass as feedstock to produce pentose and hexose sugars via hydrolysis and saccharification. The resulting compounds are then fed to microorganisms, such as *Saccharomyces cerevisiae* yeast, whose anaerobic metabolic activities result in the generation of ethanol, together with a number of byproducts and waste. These include carbon dioxide (CO_2), methanol, glycerol, lactate and acetate. The resulting ethanol is then purified and dehydrated to reduce the level of impurities and water content. The result is a high-octane fuel that meets regulatory requirements and is suitable for internal combustion engines.

Next-generation biofuels

In order to deliver biofuel at competitive prices and increase market uptake, biorefineries have begun to increase the variability of their feedstock or leverage byproducts and waste from their processes, creating integrated plants. For instance, new solutions include the latest advances in fermentation and bioprocessing. These offer a key opportunity to turn carbon-rich fluegases into new, sustainable revenue streams.

In particular, carbon-rich synthesis gas (syngas), CO_2 and methane generated by industrial activities can undergo microbial fermentation — for instance via acetogenic bacteria from the genus *Clostridium* — to obtain a spectrum of fuels and other useful organic

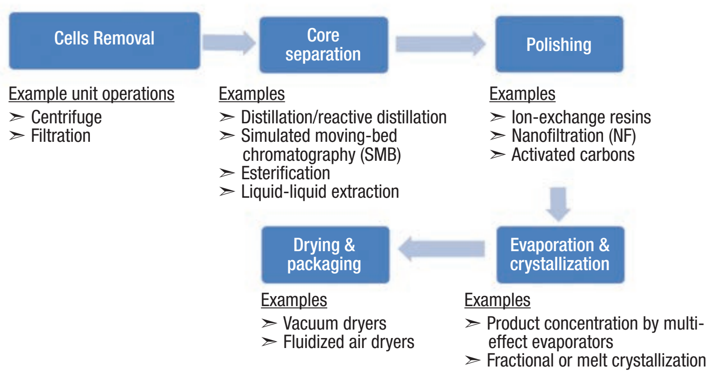

FIGURE 1. This illustration shows examples of unit operations used in some biochemical downstream-recovery process configurations

materials (Figure 2). Similarly, CO_2 from fluegas emissions can be fermented into animal proteins and nutraceuticals using chemoautotrophic bacteria, which derive energy from hydrogen. Also in these applications, separation processes follow the fermentation stage to reduce the volume of water and other impurities, as well as the microbial biomass used for the conversion.

Maximizing carbon capture

Emerging carbon capture and utilization technologies allow chemical companies and manufacturers to reduce the volume of waste carbon emitted into the atmosphere as CO or CO_2 by converting it into value-added biofuels and chemicals. Biorefining, as well as carbon capture and utilization, approaches are crucial to building a circular, net-zero or carbon-negative economy. Therefore, it is fundamental for plants to maximize their conversion rates and yields by implementing high-performance processes. In this way, businesses can optimize their energy efficiency, reducing their environmental impact and production costs while increasing market uptake. In particular, not only should the value of the targeted product exceed the recovery cost, but the energy required and resulting emissions for the entire process should be a modest fraction of the waste and emissions being captured.

One of the most challenging aspects in bioprocessing is maintaining low purification costs. In effect, while separation is not the main manufacturing stage, a number of aspects make the separation process generally account for the largest part of the total operational expenses (OPEX). Key elements contributing to these costs include: the diluted nature of the streams fed to separation units; the presence of variable and complex organic-inorganic matrices, which can have a detrimental effect on extraction; and the need to conduct the process at moderate temperatures to avoid thermal degradation of key components. As a result, the separation step can be the single largest factor influencing the overall success and commercialization of biorefineries and biological carbon-capture plants.

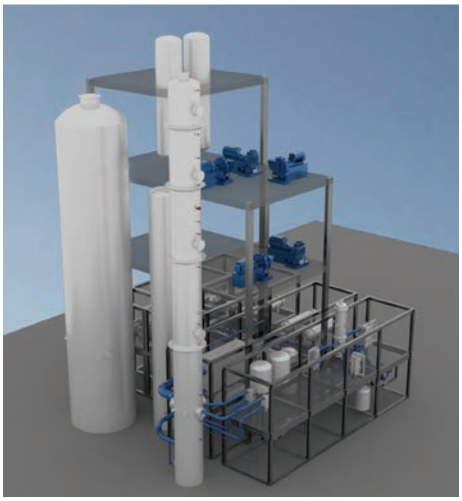

FIGURE 2. Carbon-rich syngas, CO_2 and methane generated by industrial activities can undergo microbial fermentation, followed by separation processes, to obtain a spectrum of fuels and other useful organic materials

Implementing the proper separation technologies and setups is therefore crucial for businesses to address thermal instability, high dilution and large feed variability in order to succeed in their bioprocessing strategies. In contrast to conventional petroleum refineries, where the purification unit and its structure are relatively standardized, the variability in bio-based feedstock and carbon-capture methods utilized demand that producers adopt customized solutions. Consequently, the first step to achieve the optimal solution consists of identifying the most suitable separation method for the intended application.

INDUSTRY EXAMPLE: TURNING STEEL-MILL WASTE INTO BIOETHANOL

One of the world's largest steel producers and a leading carbon recycling company were looking at ways to capture syngas produced during steel manufacturing and convert it into alcohol-based biofuels via fermentation. Key separation and mass-transfer equipment would separate fuel ethanol from the fermentation broth and remove any residual water. For this particular processing unit and fermentation broth feed, the column system would utilize structured packing.

Furthermore, integrated high-end energy-recovery systems were deployed across the various components of the distillation unit to create a closed-loop system that would recover process steam from distillation and dehydration. To further reduce the energy consumption, particularly during the dehydration of bioethanol, engineers designed a fully heat-integrated vapor-permeation unit with zeolite membranes. These offer a vapor-permeation separation process that can continuously remove permeated water, eliminating the need for additional regeneration. ❑

FIGURE 3. An important consideration in selecting column trays for biofuels applications is that the trays have anti-fouling properties

Choosing a separation method

For example, distillation is often the best option if the components in the feed have dissimilar boiling points, with differences that usually exceed 5°C, and for thermally sensitive components or substances with high boiling points, distillation under higher vacuum can be used. Conversely, affinity separation, such as liquid-liquid extraction, substantially reduces the need to distill out large volumes of water, a process that is energy intensive. Fractional crystallization can be used as a method for refining based on differences in solubilities.

A skilled process-engineering specialist can provide guidance in the selection of the most suitable method by offering detailed technical and economic evaluations on the various alternatives. Also, engineering experts can propose integrated heat- and water-recovery strategies that improve the energy and cost-efficiency of processing plants.

Defining the unit design

In addition to the type of separation method used, suitable mass-transfer components and column internals can help plants improve their processes, end-product quality and efficiency, while still handling high variability in the feedstock. More precisely, the right solution can support the creation of long-lasting, productive plants with a small footprint.

FIGURE 4. Structured packing is selected in applications that separate thermally sensitive compounds, or those that have similar boiling points

Biorefineries usually involve some degree of solids handling, and they frequently process diluted aqueous process streams with foulants. Therefore, the separation equipment should always be resistant to solids and fouling while providing the best efficiency possible. To address these issues, trays are generally used in front columns for biomass removal and concentration, followed by packed columns operated under vacuum for the purification of intermediate or end products.

Column trays have evolved over the years to accommodate bioprocessing feedstock. In particular, the industry moved from generally having no internals at all, as is the case for flask- or pot-based processes, to baffle trays, discs and donuts, as well as sieves and V-grids. For example, column trays with antifouling properties (Figure 3) are suitable for separation columns in first- and second-generation biofuel plants. Their outlet weirs are resistant to fouling and the trays can also be equipped with extra-large fixed valves developed for severe fouling applications.

Trays are also beneficial when vessel walls need periodic inspection. In this way, plants can reduce their costs and the downtime associated with repairs and maintenance, as well as extend their replacement intervals, reducing the overall environmental impact.

Once the feed streams are free of solids, mass-transfer efficiency becomes the key factor to optimize, and alternatives to trays should be considered. In effect, using such internals may result in the creation of tall, costly columns to accommodate the elevated number of theoretical stages required. Structured packing (Figure 4) is preferred in these applications.

In particular, structured packing is the go-to choice when processing thermally sensitive compounds or when substances have similar boiling points. This type of column internal minimizes liquid holdup and residence time, meaning that substances can be processed without undergoing any degradation. It also allows columns to run at a lower temperature, further protecting the thermally sensitive feed. Particularly, by featuring low liquid flowrates (and higher vapor rates), such a setup can operate at low pressure. Also, since the packing's open area is nearly as large as the column's cross-sectional surface, pressure drop is limited. This aspect also makes structured packing ideal for use in vacuum services, where the pressure drop needs to be low. These features also benefit highly corrosive services or applications where the feed may be prone to foaming. Finally, the reduced pressure drop also facilitates heat-integration concepts that improve the energy efficiency of the overall process.

Similarly, the structured packing can provide benefits in carbon capture projects, because plants can significantly reduce the size and the pressure drop across their separation column, thus reducing capital expenditure (CAPEX) and OPEX. In addition, the texture of certain types of packing can offer more uniform residence time, preventing microorganisms from the fermentation process accumulating on its surfaces, which can lead to reduced equipment service life.

Continuous improvements

In order to maintain optimum operational conditions, as well as maximize yields and energy efficiency, businesses should conduct regular servicing and maintenance on their separation equipment and seek the expertise of third-party specialists when needed. In addition, performance evaluations of existing separations trains can reveal opportunities for improvement. The most suitable and effective revamp strategies can be defined, which are key to implementing appropriate modifications to column internals and mass-transfer components and increasing overall column capacity in biorefineries and carbon-capture plants.

In order to run a successful bioprocessing plant for the production of biofuels and chemicals from sustainable resources, waste or byproducts, it is crucial to maximize energy efficiency and cost. These aspects can be addressed by developing separation solutions based on the ideal methodology, design and components. In addition, it is fundamental for businesses to keep up with the latest technological advances in order to intensify their processes and maintain a competitive edge. Holistic, proven solutions and technological expertise can support the entire lifecycle of a plant, from development through to maintenance, ensuring continuous process optimization and reliability. ■

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Using Lifecycle Cost Analysis for Best Project Value

Lifecycle cost analysis (LCCA) can be used as a tool for selecting alternatives that add the most value to a project. The methodology for implementing LCCA is described here

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Ecotek group of companies

IN BRIEF

LCCA BASICS

DISCOUNT RATE & PRESENT VALUE

LEVELIZED COST PER UNIT

LCCA AT DIFFERENT PROJECT PHASES

EXAMPLES OF LCCA

LCCA IN CIRCULAR ECONOMY

In the chemical process industries (CPI), identifying optimum process designs challenges both process and cost engineers: the first must optimize the process in terms of throughput rate, process yield and product purity (among other factors), whereas the second are responsible for estimating the costs of the different design alternatives to allow assessing their impact against the business case. Their close interaction from the beginning of the project is key, as the ability to impact cost and functional capabilities is highest in the project's early stages, where the cost of design changes is lowest [*1*].

The types of choices the design team takes throughout project development usually include: location, capacity, technology and process configuration (typically at the visualization/conceptual phase), equipment types and specifications, layout definition, utilities (typically at the conceptual/ basic engineering phase), vendor selection, construction methods, logistics and general planning (typically at the detail engineering/procurement/construction phase), and operational improvements (during operation of the plant).

In some situations, the decision is taken based on the lowest price (or lowest initial cost). This approach is better suited when comparing different bidders offering the same product or service, with little differentiation amongst the bidders (for example, civil works, where the design drawings and quantities of materials have been previously defined and included in the scope of the contract, and the bidders are selected from a short list of pre-qualified firms).

In other scenarios, there may be important differences between the evaluated alternatives in terms of capital, operations and maintenance and decommissioning costs. Here, being "cost effective" no longer means considering only the initial cost of an investment, but rather the investment throughout its entire useful life. In these cases, other techniques are better suited, such as: evaluation matrix, value-improvement practices, cash flow analysis or lifecycle cost analysis (LCCA).

The present article focuses on LCCA as a tool for selecting alternatives that add the most value to a project, describing a basic methodology for implementing an LCCA, with some examples of applications in the CPI.

NOMENCLATURE

A_0 = Amount of recurring cost
A_t = Amount of one-time cost at year *t*
Age_i = Age of component *i*
CE = Circular economy
CPU = Cost per unit
d = Real discount rate
EI = Eco-innovation
I = Initial cost
I_i = Initial cost of component i
INFLATION = Inflation rate
Li = Useful life of component i
LCC = Lifecycle cost
LCCA = Lifecycle cost analysis
LCOE = Levelized cost of electricity
MMUSD = Million U.S. dollars
NOMINAL = Nominal rate
PV = Present value
PV_B = Present value of benefits
$PV_{D\&R}$ = Present value of disposal and replacement costs
$PV_{M\&R}$ = Present value of maintenance and repair costs
PV_O = Present value of operation costs
PV_{RV} = Present value of residual value
Q_0 = Recurring annual production
Q_t = Quantity of units produced in year *t*
RV_i = Residual value of component *i*
t = Time expressed in years

LCCA basics

To put it simply, the purpose of a LCCA is to enable the project design team to select the alternative with the "least long-run cost" [*2*] and obtain the same end goal. This is done by comparing the different alternatives on a common base: total levelized cost, which

adds initial and future project costs, adjusted to take into consideration the time value of money.

The LCCA can be applied to several if not all parts of the project. As the main goal of this analysis is to provide several alternatives to pick from, the main challenge for the project design team is to find the effects of these options [3].

For example, when planning for a building, the LCCA is used to analyze the best options for transportation, materials and workforce, and it also takes into consideration the future maintenance and operational costs of the same building along with the disposal of materials that might have once been in the area (debris, trees and so on). Similarly, this method can be applied to chemical process facilities to analyze either the entire process, sections of the process, or its unit operations (for example, reactors, heaters, pumps) individually.

There are several factors that are taken into consideration when developing an LCCA, but the basics of this analysis lay on quantifying the present value of initial, operation, maintenance and repair, disposal and replacement costs, residual value and any benefits associated with each alternative, adding them along the life of the project and comparing them to the base case. To simplify the analysis, the team performing the LCCA may consider only the differences in each cost category between each evaluated alternative.

As the LCCA takes into consideration several components of a project, it is important to keep in mind that costs "are considered to be significant when they are large enough to make a big difference in the lifecycle cost" (LCC) [3], that all costs are expressed in the unit base-date currency (for example, December 2020 dollars) and that the analysis should consider the longest running part of the project (that is, if the study period is set for a time span that is shorter than the plant useful life, then the remaining useful life can be included in the analysis by means of the residual value).

Hence, even though there are different ways to determine the LCC of a project, a general formula for the LCC can be that shown by Equation 1:

$$LCC = I + PV_O + PV_{M\&R} + PV_{D\&R} + PV_{RV} - PV_B \quad (\mathbf{1})$$

Where:
LCC = Lifecycle cost
I = Initial cost
PV_O = Present value of operation costs
$PV_{M\&R}$ = Present value of maintenance
and repair costs
$PV_{D\&R}$ = Present value of disposal and
replacement costs
PV_{RV} = Present value of residual value
PV_B = Present value of benefits

The components of Equation (1) are described below:

Initial cost. The initial cost includes all capital investments to be made until the project is operational. This includes direct costs, such as equipment, materials, buildings and construction work, as well as indirect costs, such as lease, studies, permits, engineering, project management, taxes and overhead. To estimate this cost, cost engineers will require data regarding the scope and characteristics of the facilities to be constructed (such as equipment list, materials lists, work quantities) along with construction cost data with sufficient detail according to the project phase and desired precision.

Operation cost. Operation costs include all the annual costs required to run the facility, excluding maintenance and repair costs. These include raw materials, utilities (water, electricity, gas and so on), operational labor and services, and indirect costs (such as lease, insurance, security, royalties, overhead). To estimate these costs, process engineers need to develop estimates of the consumption of raw materials, chemicals and catalysts (as applicable), consumables, utilities, and workforce, whereas cost engineers need to gather data on their suppliers, local rates, as well as that of indirect costs.

Maintenance and repair cost. Maintenance and repair costs deal with the upkeep of the project itself and take into consideration that some of these costs can be annual or scheduled at several-year intervals into the future. Mechanical, instrumentation and electrical engineers may provide information regarding the maintenance requirements and frequency of the equipment involved in the project, while civil engineers may provide information about maintenance requirements for building, foundation and structural components; cost engineers then need to estimate rates and work hours for the required maintenance tasks.

There is also a risk factor to account for non-scheduled repairs (that is, corrective maintenance and resulting loss of production) that depends on failure rates of pieces of equipment. In a more detailed LCCA, this information may take into consideration results from a reliability, availability and maintainability (RAM) study.

Downtime costs (for example, loss of production, penalties and so on) due to maintenance and repairs may also be considered, if found to be significantly different between the evaluated alternatives. Process engineers usually estimate the quantity of production lost by downtime, whereas cost engineers evaluate their prices, and any penalties that may result.

Disposal and replacement costs. Disposal costs deal with the removal of existing structures or nature on site along with the transportation of wastes generated by construction or demolition (debris, residues and so on). More importantly, however, are the replacement costs. Every component of a project has a useful life, and the replacement costs are generated by removing and replacing components of the project that have completed their useful lives [*4*]. To estimate these costs, cost engineers will need, along with the list of equipment, materials and work to be installed (provided by the design team to estimate the initial costs), the useful life of each component.

Residual value. The residual value includes costs associated with the project after the study period is over. These values may be positive, negative, or zero. If the values are positive, it means that there are disposal costs attached to the end of the project (for instance, remediation costs), whereas negative values mean there is value linked to the facility at the end of the study period (for example, the plant has a useful life that exceeds the study period) and a zero value indicates no value associated at the end of the study [*5*].

For any component of the project whose useful life exceeds the study period, its residual value may be estimated (assuming linear depreciation) by using Equation (2):

$$RV_i = I_i \times \left(\frac{Age_i}{L_i} - 1\right) \quad (2)$$

Where:
RV_i = Residual value of component i
I_i = Initial cost of component *i*
Age_i = Age of component *i*
L_i = Useful life of component *i*

It is important to note that the residual value estimated by assuming linear depreciation may be considerably different from the market value that the asset will have at the end of the study period, so care should be taken when assigning this value.

Benefits. Benefits include any other value gained by the project throughout the project life. Only benefits that can be traduced into monetary value are included in the LCCA. For instance, the value of emission reduction certificates or tax incentives received from implementing one design alternative are taken into consideration. Improved image can be considered as a benefit, so long as it can be justified that it will result in improved sales or improved company value, but this is harder to demonstrate when performing projections. If the company is considering other benefits within its project evaluation criteria that cannot be directly converted to a monetary value, then the LCCA is typically accompanied by a weighed qualitative evaluation matrix to aid in the selection of the preferred design alternative.

Discount rate and present value

Present value is defined as the time-equivalent value of all cashflows from the start of the project [*5*]. As the general cost of the project is affected by costs incurred at project start (or the base year), and future costs (any year after the start of the project) these expenses have to be levelized.

Future costs are any costs incurred at any time between year one and the study period. They include recurring and one-time costs, affected by the discount rate.

One-time costs (for instance, replacement of a major equipment component) can be brought to present value using Equation (3). Recurring costs (for example, yearly operational costs) can be brought to present value using Equation (4).

$$PV = A_t \left[\frac{1}{(1+d)^t}\right] \quad (3)$$

Where:
PV = Present value
A_t = Amount of one-time cost at year "t"
d = Real discount rate
t = Time expressed in years

$$PV = A_0 \left[\frac{(1+d)^t - 1}{d \times (1+d)^t}\right] \quad (4)$$

Where:
PV = Present value
A_0 = Amount of recurring cost
d = Real discount rate
t = Time expressed in years

The effect of inflation on the real discount rate can be taken into consideration by using Equation (5).

$$d = \frac{1+NOMINAL}{1+INFLATION} - 1 \quad (5)$$

Where:

TABLE 1. TYPICAL INFORMATION AVAILABLE AND DESIGN CHOICES MADE AT DIFFERENT PROJECT PHASES

Project stage	Visualization	Conceptual engineering / feasibility study	Basic engineering	Detail engineering / EPC
Initial cost (Note 1)	Class 5	Class 4	Class 3	Class 2 / Class 1
	Based on plant type, capacity, location, cost data from previous projects based on similar technology	Based on process equipment preliminary specifications, preliminary scope of work, cost factors	Based on equipment specifications, preliminary bill of materials, preliminary work quantities, database costs	Based on equipment quotations, detailed list of materials and work quantities, construction proposals
Operation cost	Based on published data from other projects or licensors (per unit raw materials production, utilities consumption and so on)	Based on preliminary raw materials and utility balances, workforce estimates	Based on more detailed raw materials, catalyst and chemicals, utility balances, work force estimates	Based on final raw materials, catalyst and chemicals, utility balances, work force requirements
Maintenance & repair cost	Assumed as a factor or percentage of initial cost.	Assumed as a factor or percentage of initial cost and referential costs from vendors Downtime costs assumed based on similar plant availabilities	Estimated based on equipment types and useful life and/or vendor data Downtime costs may include results from RAM study	Determined from maintenance schedule for plant components Downtime costs may include results from RAM study
Disposal & replacement cost	Assumed as a factor or percentage of initial cost, at the end of the plant useful life	Considers disposal and replacement cost of major process equipment, cost factors	Considers disposal and replacement cost of equipment, major components	Considers disposal and replacement cost of equipment and other components
Residual value	Assumed based on total plant useful life	Assumed based on component categories (for example, equipment, buildings) useful lives	Estimated from individual equipment, major component useful lives. May use market values if available	Estimated from individual equipment, other component useful lives. May use market values if available
Examples of choices	• Selecting technology / licensor • Selecting site • Defining business strategy / logistics • Selecting contracting scheme	• Selecting process configuration • Selecting different types of equipment • Defining energy and utility systems • Selecting pollution prevention / control technologies	• Selecting suppliers for long-lead items • Evaluating proposals from general contractors • To complete a value improvement analysis	• Selecting suppliers for equipment / materials • Selecting construction methods / planning • Sourcing utilities / materials for operations phase

Note 1: Based on AACE Recommended Practice 18R-97 [6]

d = Real discount rate
$NOMINAL$ = Nominal rate
$INFLATION$ = Inflation rate

Ref. 5 contains a more detailed discussion of time-value of money.

Levelized cost per unit

Another useful way to express LCC comes in the form of a levelized cost per unit (CPU). This is obtained by dividing the total lifecycle cost by the levelized units produced by the plant throughout the period in the study, yielding a value in terms of cost per ton, cost per barrel, cost per kilowatt-hour, or any other unit of significance to the plant output, as calculated on Equation (6). In Equation (6), it is worthy to note that production in future years is also adjusted using the discount rate.

$$CPU = \frac{LCC}{\sum Q_t\left(\frac{1}{(1+d)^t}\right)} \qquad (6)$$

Where:
CPU = Cost per unit
Q_t = Quantity of units produced in year t

If the annual production is assumed constant throughout the entire evaluation period, then Equation (6) can be simplified to Equation (7):

$$CPU = \frac{LCC}{Q_0\left[\frac{(1+d)^t-1}{d\times(1+d)^t}\right]} \qquad (7)$$

Where:
Q_0 = Recurring annual production

The benefit of expressing the LCC in cost per unit form is that it allows the project design team to compare each option against benchmarks for other plants or technologies.

LCCA at different project phases

An LCCA may be performed at different project phases (for example, visualization, conceptual engineering and so on), with varying degrees of available information, to aid in different design choices. Table 1 shows an example of the type of information available and some typical choices that can be made with LCCA at different project phases (Note: this table is to be used as a general guideline only, as different information may be made available at different project stages depending on how the project is planned).

Examples of LCCA

The following examples of LCCA can be used to illustrate the usefulness of LCCA for some project design choices. The values in the following examples have been slightly altered or simplified from real project data

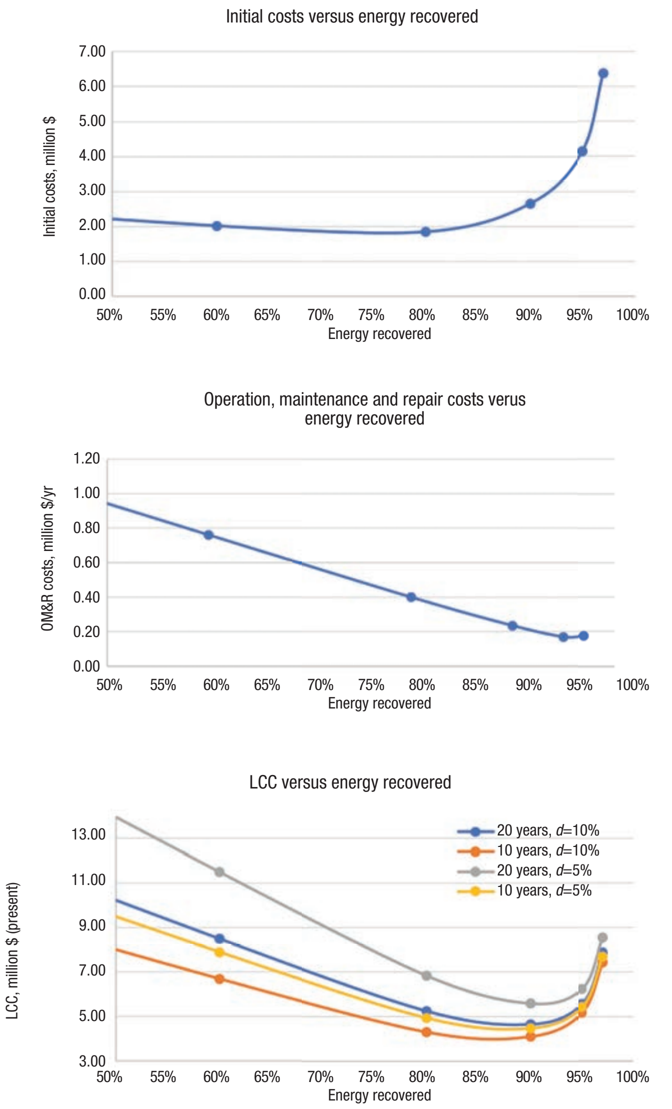

FIGURE 1. The data and results of Example 2 are plotted in these three graphs for illustrative purposes.

Examples of LCCA 1: Reducing costs at an operating plant — energy recovery with a high-pressure gas expander. In this example, a high-pressure gas stream is currently being expanded in a pressure-reduction valve. Plant management is evaluating the installation of an expander to recover energy from the gas and use it to generate electricity that would be consumed inside the plant. The current electricity price forecast can be approximated as an average of \$72/MWh (or 7.2 ¢/kWh) for the entire study period.

Based on the gas flowrate and process conditions, it is estimated that a 280-kW expander can be installed, with said expander being capable of generating 2,350 MWh of energy each year. The total cost of the installation, including procurement of equipment and materials, transportation, construction works and modifications to the existing facilities, commissioning, startup and indirect costs was estimated at \$476,000.

The expander is based on a magnetic-drive technology with almost no moving parts. No additional operations personnel are needed. Maintenance and repairs costs are also very low, with the expander not requiring maintenance in the first ten years. Yet for evaluation purposes, the team decides to assume a cost of 3% of the initial costs for maintenance and repairs each year. Insurance costs are assumed negligible, as the asset will be covered by the plant overall insurance policy.

The expander has a useful life of 20 years, yet the project will be evaluated at 10 years, at a 10% real discount rate. Linear depreciation is considered for calculation of the residual value.

In this example, the base case (no expander) LCC is calculated by adding the present value operational cost of the electricity consumed throughout the study period. Given that electricity consumption is a recurring cost, Equation (4) is used:

$$PV_{O,base\ case} = 2{,}350\text{ MWh} \times \$72/\text{MWh}\ [(1 + 0.1)^{10} - 1]/[0.1 \times (1 + 0.1)^{10}]$$

$$PV_{O,\ base\ case} = \$1{,}039{,}661.$$

Other components of the *LCC* can be assumed as zero. Hence, the *LCC* for the base case, using Equation (1), is:

$$LCC_{base\ case} = \$1{,}039{,}661.$$

For Alternative 1 (with expander), the initial cost is the total installed cost of the expander:

$$I_{alternative\ 1} = \$476{,}000$$

The operation cost can be considered negligible in this example, whereas the maintenance and repairs costs are recurring costs:

$$PV_{O,alternative\ 1} = \$0$$

$$PV_{M\&R,alternative\ 1} = 0.03 \times \$476{,}000\ [(1 + 0.1)^{10} - 1]/[0.1 \times (1 + 0.1)^{10}] = \$87{,}744$$

Disposal and replacement costs in this example are negligible. The residual value is calculated using Equation (2):

$$PV_{RV,alternative\ 1} = \$476{,}000 \times [(10/20) - 1] = -\$238{,}000$$

This value is brought to present value by using Equation (3) at year 10:

$$PV_{RV,alternative\ 1} = -\ \$238{,}000\ [1/(1 + 0.1)^{10}] = -\ \$91{,}759$$

Additional benefits in this example are negligible.

Then, the *LCC* for Alternative 1 is, from Equation (1):

$$LCC_{Alternative\ 1} = \$476{,}000 + 0 + \$87{,}744 + 0 - \$91{,}759 - 0 = \$471{,}985$$

Hence, given that the *LCC* for alternative 1 is lower than

TABLE 2. DATA FOR EXAMPLE 2

Design Option	Unit	No Recovery	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Heat recovered in heat exchangers	%	0%	60%	80%	90%	95%	97%
Initial costs	million $	3.29	2.02	1.84	2.66	4.13	6.37
Operation, maintenance and repairs costs	million $/ year	1.85	0.76	0.40	0.24	0.17	0.17

TABLE 3. CALCULATED LCC FOR EXAMPLE 2

Design Option	Unit	No Recovery	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Heat recovered in heat exchangers	%	0%	60%	80%	90%	95%	97%
LCC at 20 years, *d* =10%	million $	19.07	8.49	5.25	4.66	5.58	7.85
LCC at 10 years, *d* =10%	million $	14.68	6.69	4.30	4.10	5.18	7.44
LCC at 20 years, *d* =5%	million $	26.39	11.50	6.83	5.59	6.25	8.54
LCC at 10 years, *d* =5%	million $	17.60	7.89	4.93	4.47	5.45	7.71

the base case, the project provides economic benefits to the facility (over $560,000 savings in electricity in present value, for a 10-year period).

The management may also be interested in calculating the levelized cost of electricity (LCOE) for the expander, to compare against the current cost of electricity from the grid or other power generation options. In this example, the LCOE is equivalent to the cost per unit as defined in Equation (7):

$LCOE_{alternative\ 1}$ = (\$471,985)/{2,350 MWh[$(1 + 0.1)^{10}$ – 1]/[0.1 × $(1 + 0.1)^{10}$]}
= \$33/MWh
= 3.3 ¢/kWh

Therefore, in this example, the cost of electricity from the expander is 55% lower than the cost of electricity from the utility.

If management now wishes to evaluate the *LCC*, energy savings and *LCOE* over the expander useful life (20 years), repeating the above calculations with *t* = 20 years yields the following results:

$LCC_{base\ case,20years}$ = \$1,440,495
$LCC_{alternative\ 1,20years}$ = \$597,574
Savings versus base case, at present value = \$842,921
$LCOE_{alternative1,20years}$ = \$30/MWh = 3 ¢/kWh

Example 2: Finding the optimum design — thermal energy recovery at a plant preheat train. In this example, the preheating section of a plant is composed of heat exchangers and a furnace located upstream of the reactor. The heat exchangers will transfer heat from the reaction products to the reactants, and the furnace will cover the last heat addition to reach the required reactor inlet temperature. The design team is now trying to select the optimum design (that is, the amount of heat recovered at the heat exchangers that generates the lowest LCC), taking into consideration the limitation that the furnace design duty must be kept above a minimum value for plant startup.

After interaction between process and cost engineers, the team estimates the initial, operations, maintenance and repair costs included in Table 2. Disposal and replacement costs, and residual value are determined not to be significantly different between each alternative, and additional economic benefits are found to be negligible. The design team will perform the evaluation at study periods of 10 years and 20 years, and real discount rates of 10% and 5%.

In this example, to obtain the optimum design, the team needs to calculate the present value of the recurring operations, maintenance and repairs costs by using Equation (4) for each study period and discount rate evaluated, and then obtain the LCC for each option using Equation (1). The results are shown on Table 3.

As can be seen in Table 3, Alternative 3 (90% of heat recovered) presents the minimum LCC for this example and is thus the favorable option among those considered in the LCCA. However, the design team may choose to plot the costs of Tables 2 and 3 against the optimized variable (energy recovered in the heat exchangers), as seen in Figure 1.

From Figure 1, the following behavior can be observed:

- **Initial costs increase exponentially as the efficiency approaches 100%.** In this example, the reason for this cost increase lies in the fact that as more energy is recovered in the heat exchangers, the log mean temperature difference becomes smaller, thus requiring larger heat transfer area. This cost increase behavior is exhibited by many other unit operations, such as mass transfer or separation (for example, cost increases significantly when aiming to increase the purity of one product from 90% to 99%, and then to 99.9%).
- **Future cost savings are not necessarily linear with increasing efficiency.** In this example, each new heat exchanger reduces operation, maintenance and repair costs for the plant in an almost linear manner until a point (near 95% energy recovery), when cost reduction becomes smaller or costs start to increase. In this example, the additional cost of maintenance to clean the heat exchangers (and to a lesser extent the additional electrical consumption in pumps to overcome pressure losses) outweighs fuel-gas cost savings after this point. This behavior can also be seen in many other cases, as

benefits (or in this case, cost reductions) typically follow the law of diminishing marginal returns.

- **The LCC plotted against the optimized variable forms a U-shaped curve with a clear optimum.** This optimum value is influenced by the study period, as well as the discount rate. In this example, the optimum value for a 10-year period at a 10% discount rate is near 85% energy recovery, whereas the optimum for a 20-year period at a 5% discount rate is closer to 92% energy recovery. Generally, shorter study periods and higher discount rates favor alternatives with lower initial costs, whereas larger time horizons and lower discount rates favor alternatives with lower recurring future costs.

LCCA in circular economy

In the previous sections the LCCA has been described and broken down to its most important parts. By this point, we know that there are typically six main components to the lifecycle cost of a project, and that defining them requires close interaction between the project design team (with process engineers having a lead role) and cost engineers at different project phases, and an important amount of forecasting. The multidisciplinary and forward-looking nature of this type of analysis lends itself to the innovation of green solutions.

In today's economy, there are many aspects to be considered, with the transition toward cleaner energies and processes gaining importance. This transition not only considers moving from fossil fuels to sustainable energies, but brings on new terms such as "circular economy" and "eco-innovation."

Eco-innovation (EI) is defined as any innovation that leads toward a sustainable, or durable, development [8], while circular economy (CE) is defined as a strategy to close economical loops on a permanently regenerative economy to rethink the lifecycle of a product [9]. In other words, one aims to create new eco-friendly solutions while the other plans for them to come into a full circle and generate profit all around.

As mentioned before, the LCCA is the breakdown of a project in which the best economic and business alternatives throughout a project's life are studied. The LCCA comes almost naturally to the implementation of both EI and CE, because it is a tool through which alternatives (such as the recycling of parts) can be planned from a very early stage.

Additionally, by creating a broader picture of the project's life we are enabled to plan and prepare for gains and possible losses from the very beginning. This is applied with the main idea behind eco-innovation to enhance performance through ecotechnologies and enter already existing markets [8], as it provides a sort of plan of action. The LCCA not only aids entrance into the market but gives the innovator an upper hand for the typical "and then what?" questions posed by investors.

This is particularly true for markets where companies are being encouraged to take these new, greener routes [9] in order to reduce environmental impacts. Moreover, closing "loose ends" is an asset to any project as the current market aims to gain competitiveness by minimizing

the waste of materials and energy [8] while increasing efficiencies and productivity.

As our world adapts to the new idea and commitment to an environmental transition, and all its new terms and laws, the LCCA plays a key role in determining who will have a competitive advantage in the market. ■

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Choosing Footwear for Chemical Working Environments

Selecting footwear for plant personnel is not a "one size fits all" situation — various factors must be considered to ensure the best shoe for a specific application

Xavier Kawula
Honeywell Industrial Footwear

Chemical manufacturing plants generally have questions about their overall safety protection program, of which footwear is a foundation (Figure 1). Employers and workers want to avoid injuries while on the job, but standing for long periods of time can lead to tired, accident-prone feet. So which product features, especially when working with chemicals, should plants take into consideration when it comes to shoes?

Chemical compatibility

The chemical compounds used in footwear have basic affinities or lack of affinities for certain chemicals, based on how they are made. Chemicals similar to the compound from which the footwear is constructed make that compound break down faster. For example, rubber, a common material used in footwear, is petroleum-based. Therefore, any substance that has oily content, such as gasoline or cutting oils, is going to break down the rubber faster than other compounds. Simply put, rubber is typically made from petroleum, so oily materials will more quickly break down the rubber compound. This is important to take into consideration for workers in the food-processing industry where oils (in the form of vegetable or animal fat) are prevalent. Workers in food-processing facilities should look for a polyvinylchloride (PVC) boot, since PVC will withstand those chemicals in their work environment much better.

Conversely, industries that work with materials such as alcohol and ammonia should choose a rubber boot, because these chemicals break down PVC comparatively quickly. Acids and bases are so varied in their impact on boot materials that there can be no single rule, as organic and mineral acids have wide-ranging effects. These chemicals need to be evaluated on a case-by-case basis to determine which footwear material is the proper choice.

Features to consider holistically

When looking to purchase footwear for the job, you cannot simply look at the upper material. It is important to look at the overall boot and make evaluations based on the specific job at hand. Managers must look at physical durability, chemical durability, slip resistance and comfort.

Finding the right shoe involves the right fit and protection for specific personnel duties, and is not based solely on the wearer's occupation. Someone who is on their feet walking all day will require shoes that offer comfort and protection features related to being on one's feet for long periods of time. Others may need more slip resistance. Therefore, it is important to evaluate the overall need and determine what is most important. Weighing durability against the chemical wear and tear based on your job is one part of the decision around which type of footwear is best. It is important to think of the different work environments that personnel will encounter and determine which features are most important.

Slip resistance is key

Slip resistance or traction is a feature that is very important to consider. Selecting appropriate slip-resistant footwear can be challenging, because there is a lot of industry frustration and confusion around slip ratings and what is best. Many products will say they are slip-resistant or call out their slip resistance as "fair," "good," or use another subjective term. If plants are looking for footwear to be compliant with a Slip Hazard Assessment Plan, it is important to be able to review the manufacturer's actual slip scores in the standardized tests. The current standard for slip-resistant testing has been developed by SATRA Technology (Kettering, U.K.; www.satra.com), which is a whole-shoe test. Older tests were designed to test the floor, not the shoe, and are now considered obsolete.

Slip-resistance certifications are typically divided into three categories (Table 1): SRA, SRB and SRC. It is recommended to select a shoe with SRA qualification for most wearing occasions, and an SRC slip-rated outsole when looking for best-in-class slip performance. If an outsole has a passing score on the Slip Resistance A test — soapy water on

FIGURE 1. A variety of product features are available when selecting industrial footwear, and special consideration must be taken to choose the best shoe for a specific chemical-handling job

TABLE 1. TESTING LEVELS FOR SLIP RESISTANCE

SRA	Tested for slip on ceramic tile wetted with a soapy solution
SRB	Tested for slip on stainless steel wetted with glycerol
SRC	Combination of SRA and SRB tests

quarry tile — it can be labeled SRA. If an outsole has a passing score on the Slip Resistance B test — glycerol on stainless steel — it can be labeled SRB. If it passes both tests, it can be labeled as SRC.

Environmental testing

It is critical to test boots in the environment that they are intended to be worn (Figure 2). Sometimes it is not the first contaminant that is the problem. The contaminant itself could be relatively easy to work with but the cleaning material for the environment could pose problems. Bleach is often used as a cleaning agent, and bleach can be damaging to rubber, so a suggestion would be a dipped-neoprene or PVC product in that case. That is why it is always best to make sure products are tested on site to monitor potential cross-contamination. A good example of this is workers at hydraulic fracturing (fracking) sites. Fracking fluids are often proprietary, so footwear providers do not know exactly what chemical compounds are contained within them. Fracking fluids are highly volatile, and counteracting solutions in such sites need to be tested with the footwear to ensure safety.

Inspection and cleaning

Do you have an inspection or safety survey in place to examine the boots to make sure they are being replaced at the right rate for the wear and tear based on the job? This is really important to ensure the safety of workers. The last and best thing to do with any boot is to make sure to wash them with clean, clear water after any working cycle. Any chemical that sits on the boot for some time will wear it down. The best cleaning agent is simply water.

New innovations on the horizon

As footwear design evolves, there are some innovations quickly coming down the pike that will greatly increase comfort and durability. The first is climate control. What we are seeing is that workers are becoming more sophisticated in their understanding of how to protect themselves from the cold. In the past, people have looked for temperature ratings, thinking that more protection is always best. Instead, the industry is seeing a trend to look for climate control in the boots rather than simple insulation. High insulation values that cause one to perspire create a worse condition than the cold itself, as perspiration condenses, drawing even more heat out of the body, especially when the person goes from an active to inactive state.

FIGURE 2. A best practice in footwear selection is to test the boot in the specific environment where it will be used

The second innovation is ergonomic design. Footwear design and production often err on the side of simplifying production, as the boots are mass-produced versus custom-made. The goal of the near future of boot making will be to deliver a product that has a customized fit with no break-in time.

As worker health and comfort become a greater focus for maintaining productivity, footwear needs to be a main part of the solution. Remember to look first at the overall job and working environment to determine what features (physical durability, chemical durability, slip resistance and comfort) are most important. Next, make sure that there is a system in place to properly test footwear, as well as inspect when the boots need to be replaced. Lastly, cleaning boots on a regular basis with clean, clear water will extend their lifespan and durability against exposure to chemicals. ■

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Economic Indicators

2018 2019 2020

Download the CEPCI two weeks sooner at www.chemengonline.com/pci

CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957–59 = 100)	Sept. '20 Prelim.	Aug. '20 Final	Sept. '19 Final
CE Index	593.8	594.1	603.6
Equipment	717.3	718.1	733.7
Heat exchangers & tanks	605.8	608.2	637.0
Process machinery	718.0	718.4	723.5
Pipe, valves & fittings	954.0	955.3	960.6
Process instruments	422.1	416.9	422.8
Pumps & compressors	1084.0	1084.0	1073.5
Electrical equipment	565.0	563.5	561.8
Structural supports & misc.	752.7	756.1	785.9
Construction labor	338.0	340.9	338.4
Buildings	616.2	601.7	592.3
Engineering & supervision	312.3	312.1	314.0

Annual Index:

2012 = 584.6

2013 = 567.3

2014 = 576.1

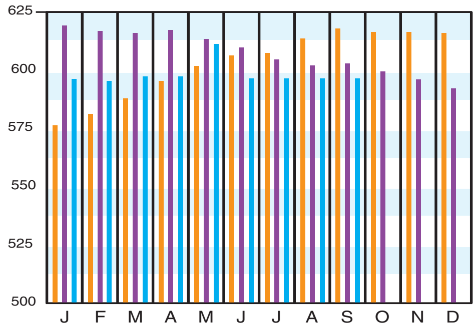
2015 = 556.8

2016 = 541.7

2017 = 567.5

2018 = 603.1

2019 = 607.5

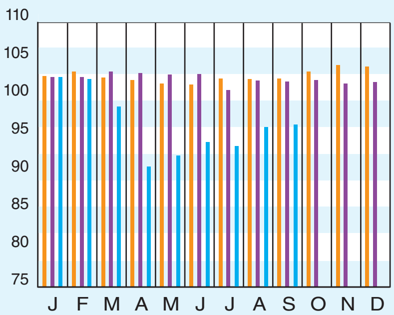


Starting in April 2007, several data series for labor and compressors were converted to accommodate series IDs discontinued by the U.S. Bureau of Labor Statistics (BLS). Starting in March 2018, the data series for chemical industry special machinery was replaced because the series was discontinued by BLS (see *Chem. Eng.*, April 2018, p. 76–77.)

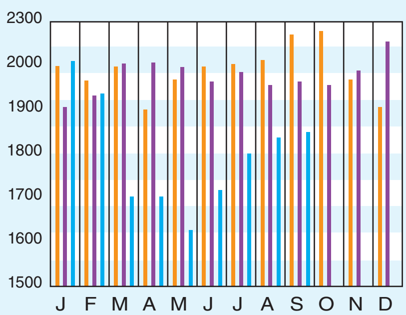
CURRENT BUSINESS INDICATORS

	LATEST	PREVIOUS		YEAR AGO
CPI output index (2012 = 100)	Sept. '20 = 96.2	Aug. '20 = 96.1	Jul. '20 = 94.2	Sept. '19 = 102.4
CPI value of output, $ billions	Sept. '20 = 1,839.8	Aug. '20 = 1,835.6	Jul. '20 = 1,808.9	Sept. '19 = 2,018.1
CPI operating rate, %	Sept. '20 = 71.8	Aug. '20 = 71.6	Jul. '20 = 70.1	Sept. '19 = 76.3
Producer prices, industrial chemicals (1982 = 100)	Oct. '20 = 226.5	Sept. '20 = 227.3	Aug. '20 = 219.5	Oct. '19 = 252.3
Industrial Production in Manufacturing (2012 =100)*	Sept. '20 = 98.3	Aug. '20 = 98.5	Jul. '20 = 97.4	Sept. '19 = 104.5
Hourly earnings index, chemical & allied products (1992 = 100)	Oct. '20 = 188.9	Sept. '20 = 191.9	Aug. '20 = 188.8	Oct. '19 = 187.8
Productivity index, chemicals & allied products (1992 = 100)	Sept. '20 = 101.2	Aug. '20 = 99.9	Jul. '20 = 100.8	Sept. '19 = 97.0

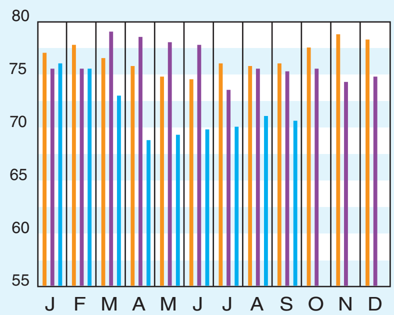
CPI OUTPUT INDEX (2000 = 100)†



CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)



*Due to discontinuance, the Index of Industrial Activity has been replaced by the Industrial Production in Manufacturing index from the U.S. Federal Reserve Board.
†For the current month's CPI output index values, the base year was changed from 2000 to 2012
Current business indicators provided by Global Insight, Inc., Lexington, Mass.

CURRENT TRENDS

The preliminary value for the *CE* Plant Cost Index (CEPCI; top) for September 2020 (the most recent data available) decreased by a small margin compared to the previous month's value. It continues a period of up-and-down fluctuations in the CEPCI values. The Equipment and Construction Labor subindexes declined in September, while the Buildings and Engineering & Supervision subindexes increased. The current CEPCI value now sits at 1.6% lower than the corresponding value from September of last year. Meanwhile, the Current Business Indicators (CBI; middle) showed a small decrease in producer prices and hourly earnings for October, but the timing of this month's production schedule did not allow updates for all values.